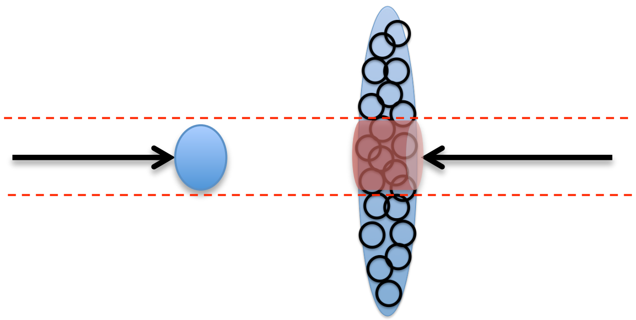


New results of proton-nucleus (pA) collisions at CMS

Wei Li

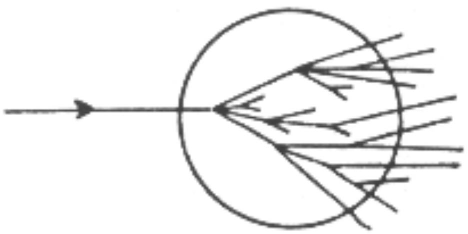
Rice University

P-25 Seminar, LANL, April 2013

Why studying pA collisions?

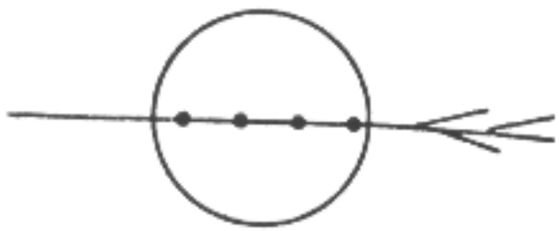
Study of pA collisions started back in early 1970’s and its role has been evolving since then

A reference to study particle production mechanism in pp



$\langle n \rangle_A \sim \langle n \rangle_p A^{1/3}$

or

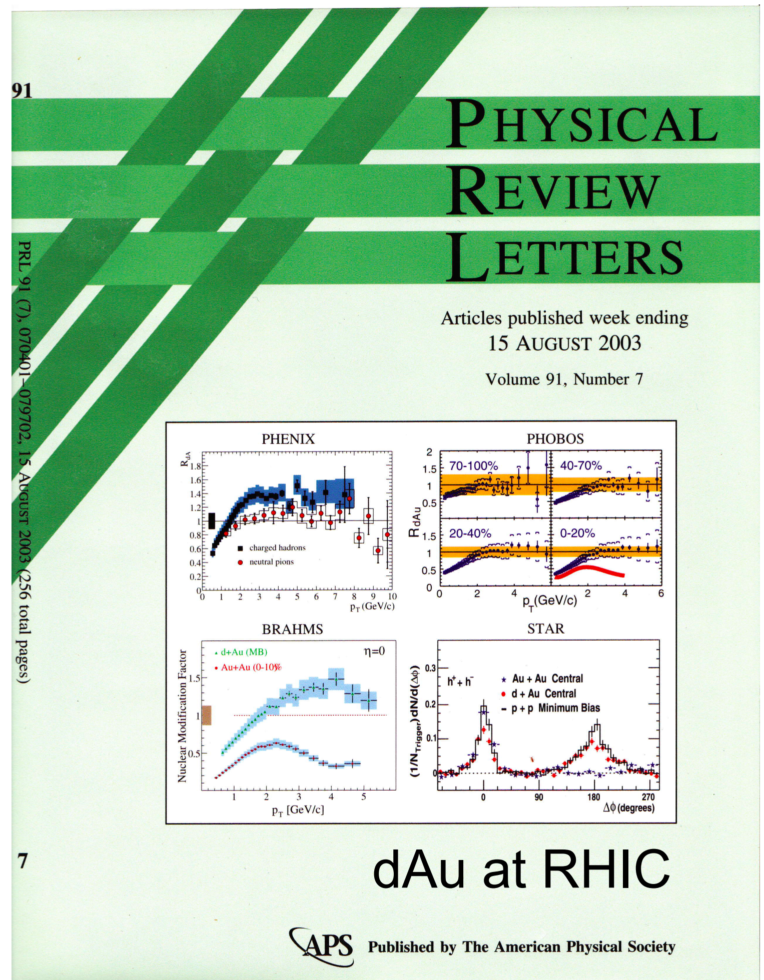


$\langle n \rangle_A \sim \langle n \rangle_p$ or

$\langle n(A,s) \rangle \sim \langle n(p,\bar{\sqrt{s}}) \rangle$

A lot of puzzles; gluon was not known

Late 1980’s till 2000’s, “cold nuclear matter” effect as a reference of “hot nuclear matter” in nucleus-nucleus (AA)



dAu at RHIC

Game Change: the “ridge” in pp collisions

Opportunity of studying novel QCD phenomena opened up by the LHC

Two-particle Δη-Δϕ correlation

September, 2010

PUBLISHED FOR SISSA BY SPRINGER

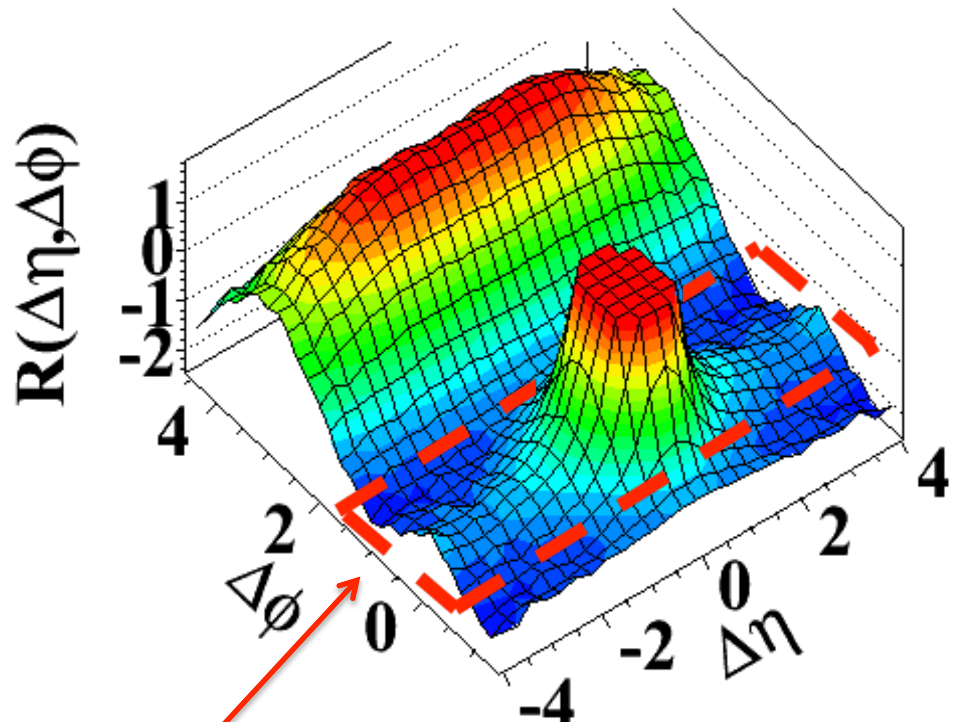
RECEIVED: *September 22, 2010*
ACCEPTED: *September 23, 2010*
PUBLISHED: *September 27, 2010*

Observation of long-range, near-side angular correlations in proton-proton collisions at the LHC

The CMS collaboration

ABSTRACT: Results on two-particle angular correlations for charged particles emitted in proton-proton collisions at center-of-mass energies of 0.9, 2.36, and 7 TeV are presented, using data collected with the CMS detector over a broad range of pseudorapidity (η) and azimuthal angle (ϕ). Short-range correlations in $\Delta\eta$, which are studied in minimum bias

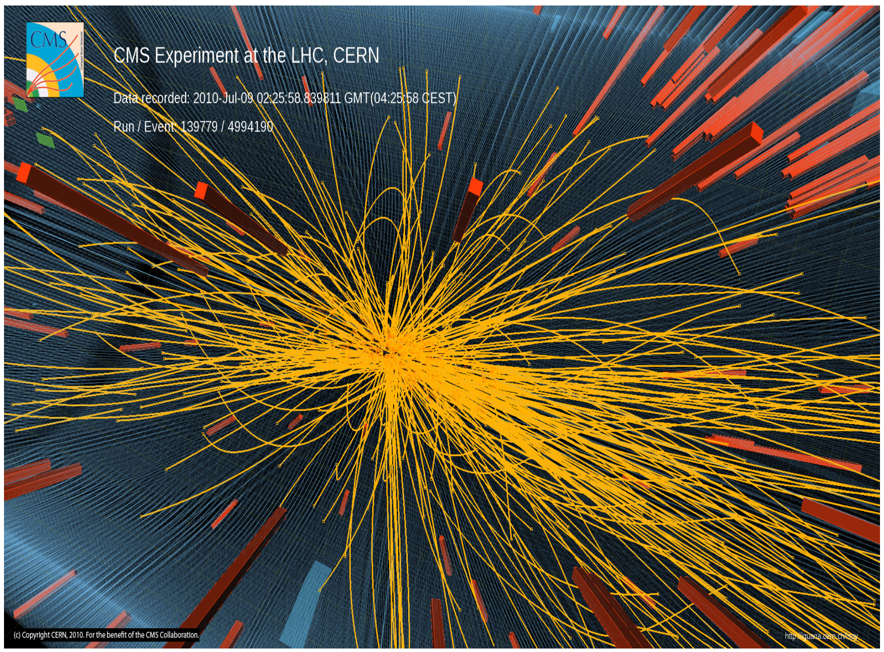
pp N>110, 1<p_T<3 GeV/c



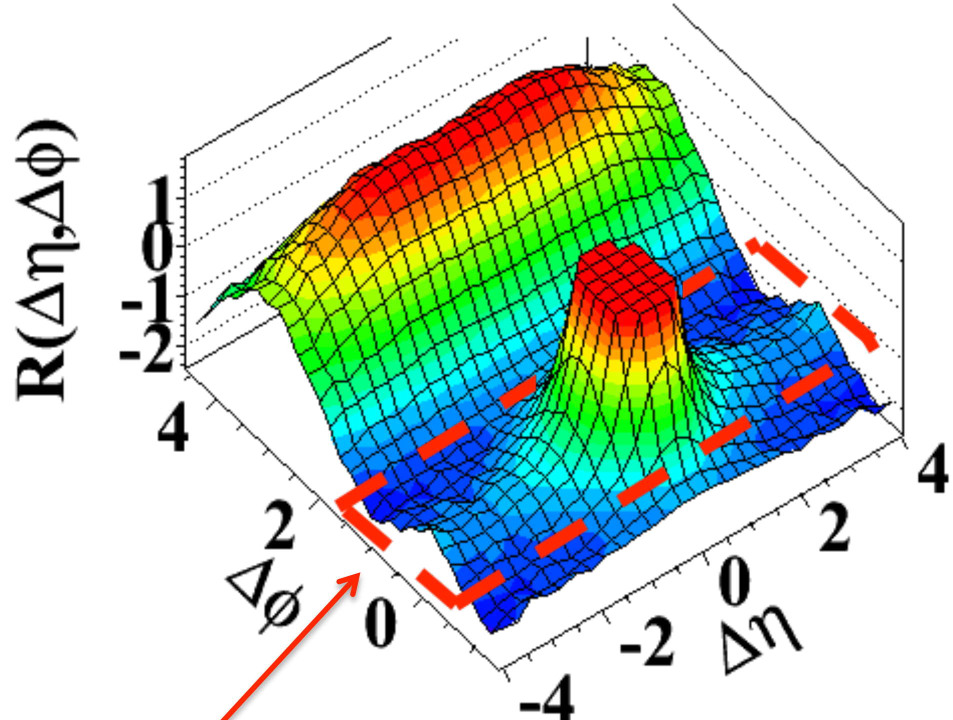
Unexpected ridge-like correlations in high multiplicity pp!

The “ridge” in pp collisions

Two-particle Δη-Δϕ correlation



pp N>110, 1<p_T<3 GeV/c



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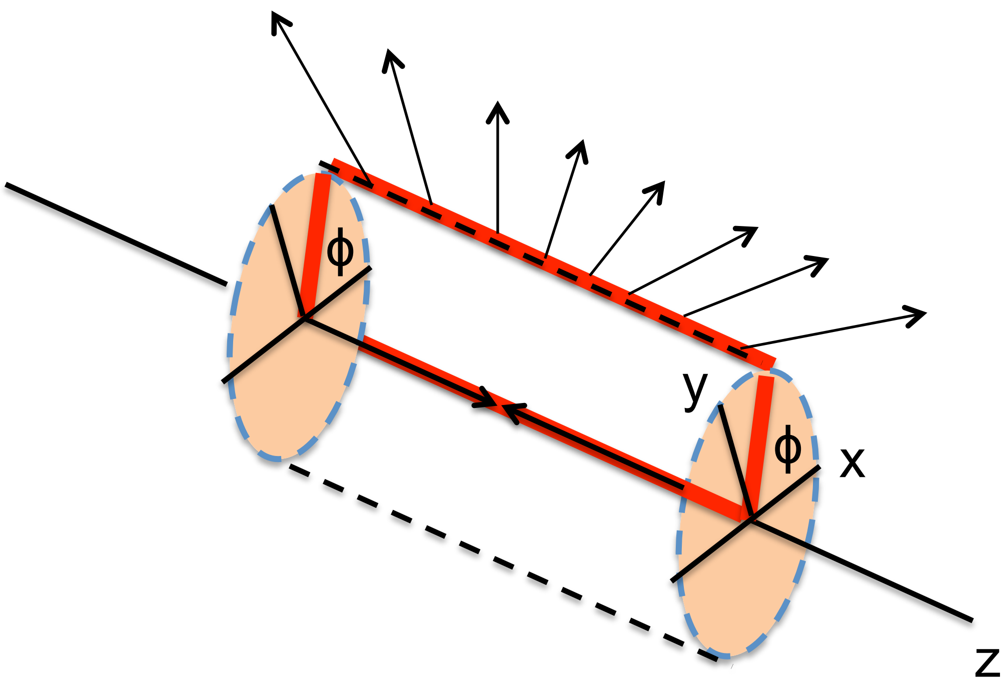
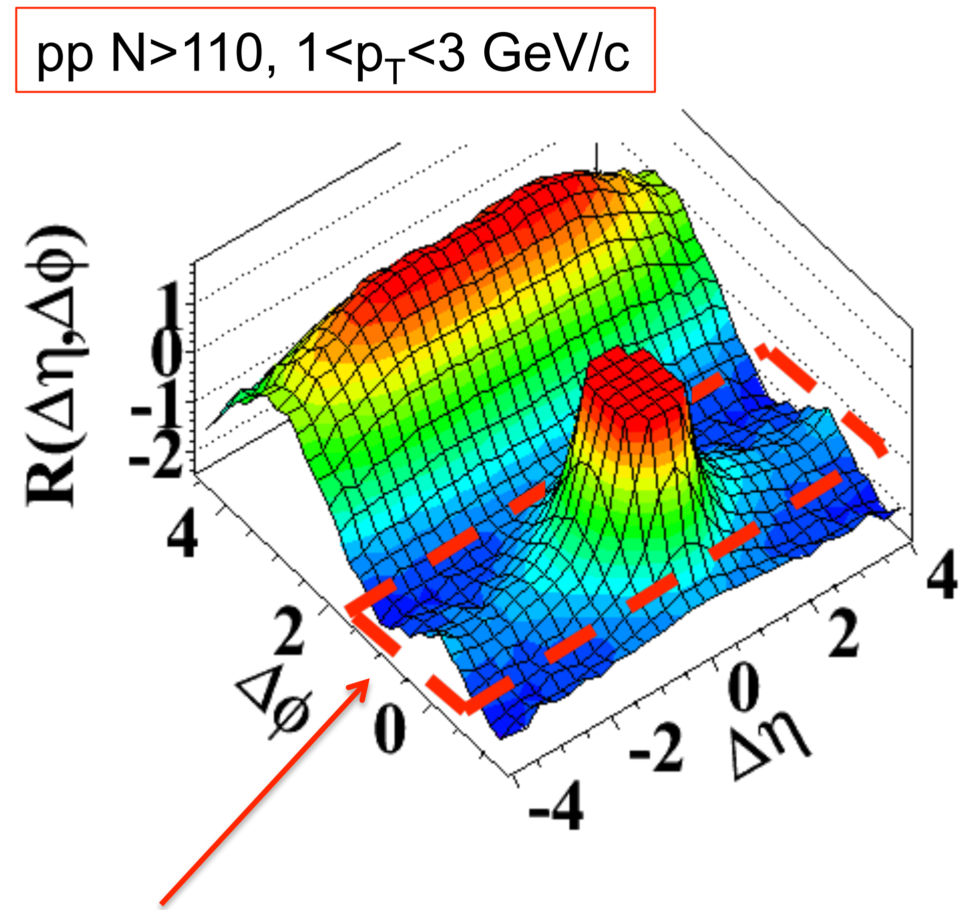


A preferred plane for particle emission

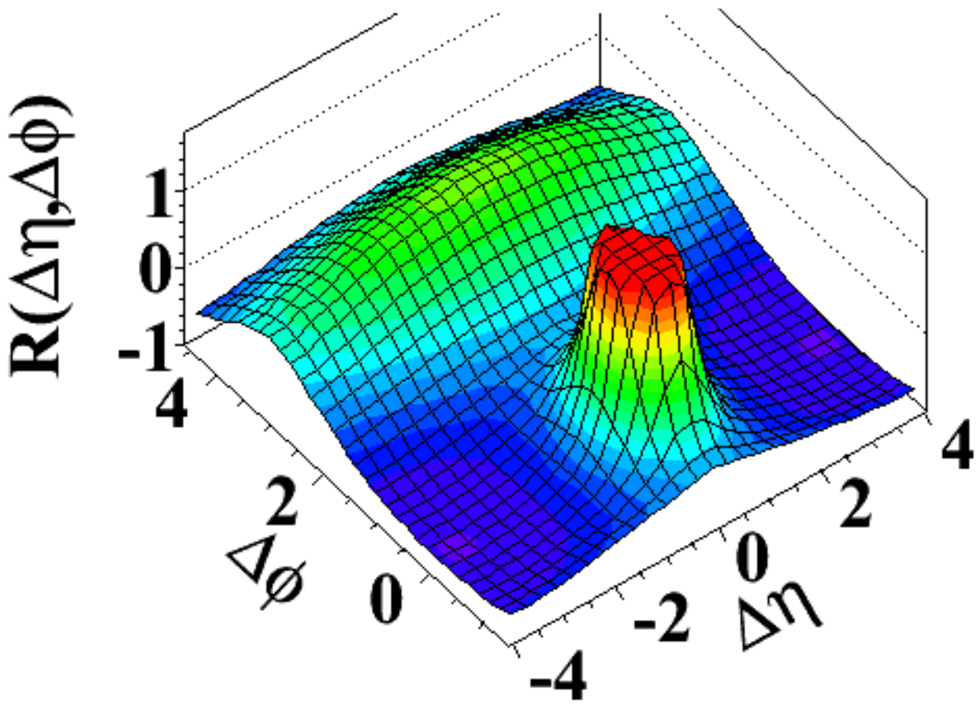


Unexpected ridge-like correlations in high multiplicity pp!

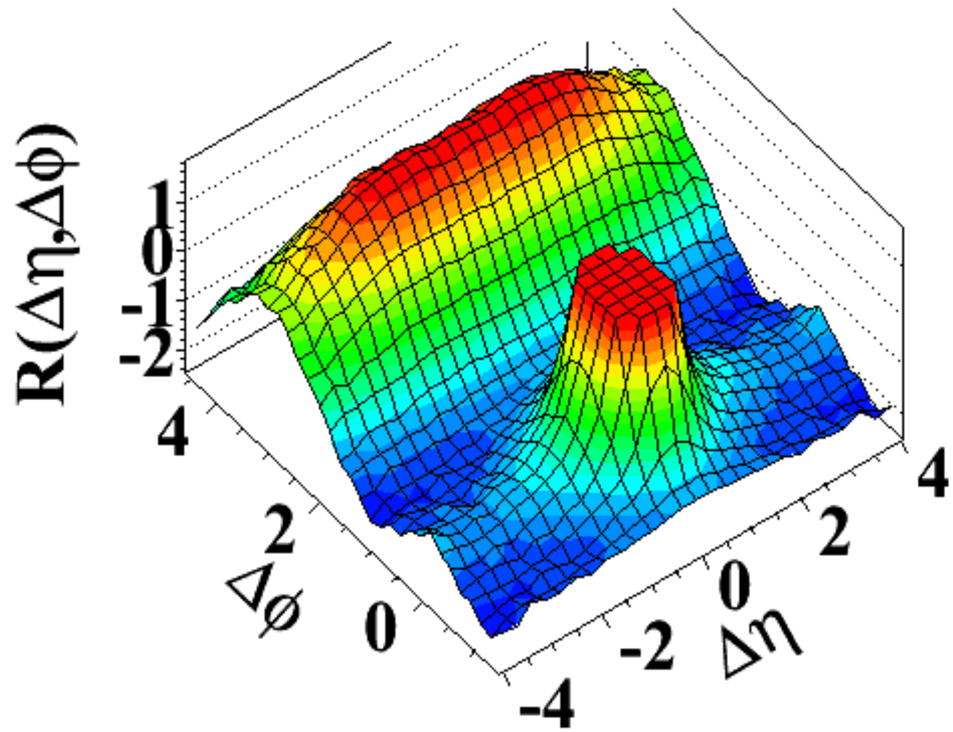
The "ridge" in pp collisions

Two-particle Δη-Δϕ correlation

pp <N>~15, $1<p_T<3$ GeV/c



pp N>110, $1<p_T<3$ GeV/c



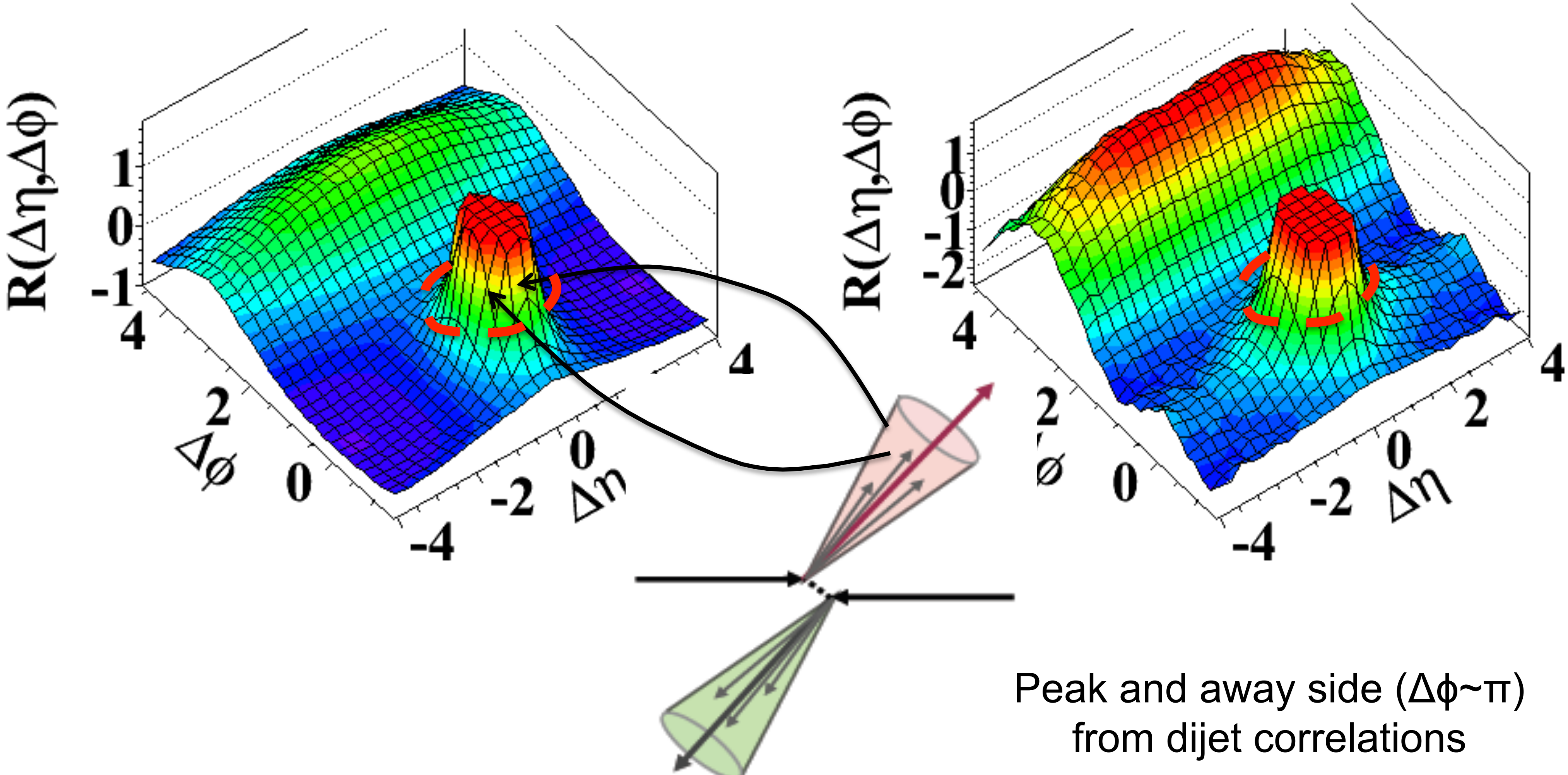
No ridge observed in minimum bias pp or any pp MC generators

The “ridge” in pp collisions

Two-particle Δη-Δϕ correlation

pp <N>~15, $1<p_T<3$ GeV/c

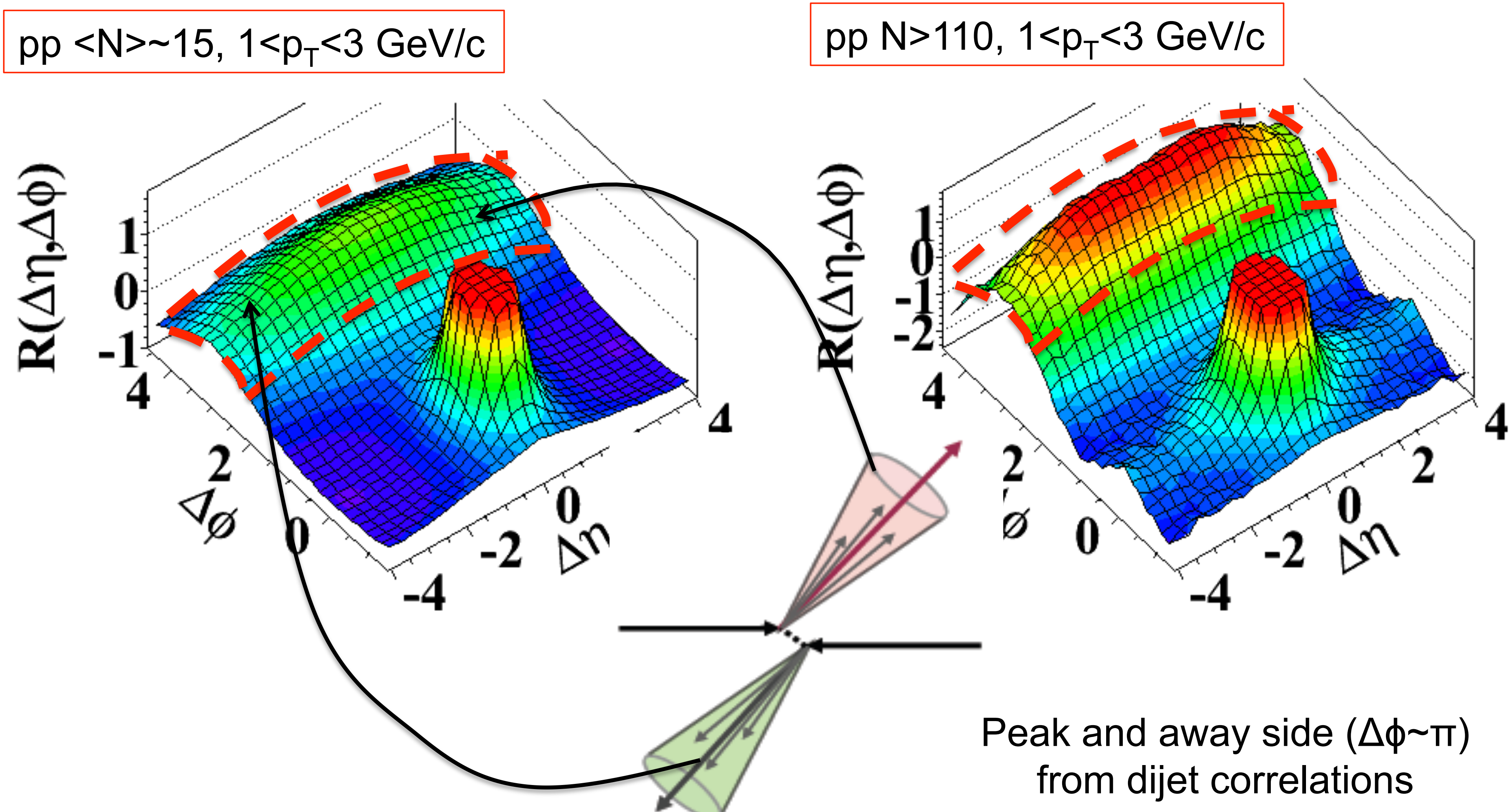
pp N>110, $1<p_T<3$ GeV/c



Peak and away side (Δϕ~π)
from dijet correlations

The “ridge” in pp collisions

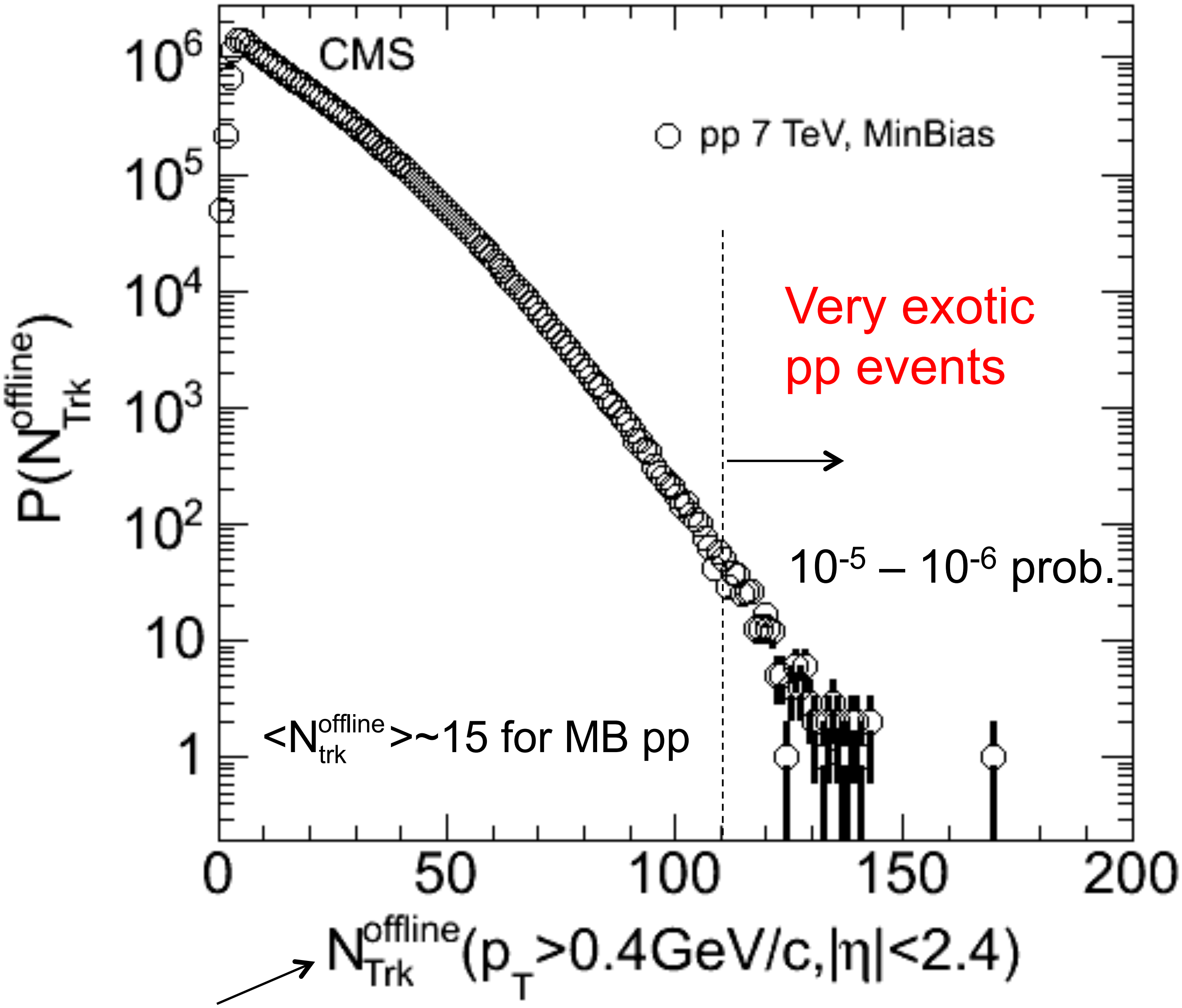
Two-particle Δη-Δϕ correlation



Peak and away side (Δϕ~π)
from dijet correlations

Very high multiplicity pp collisions

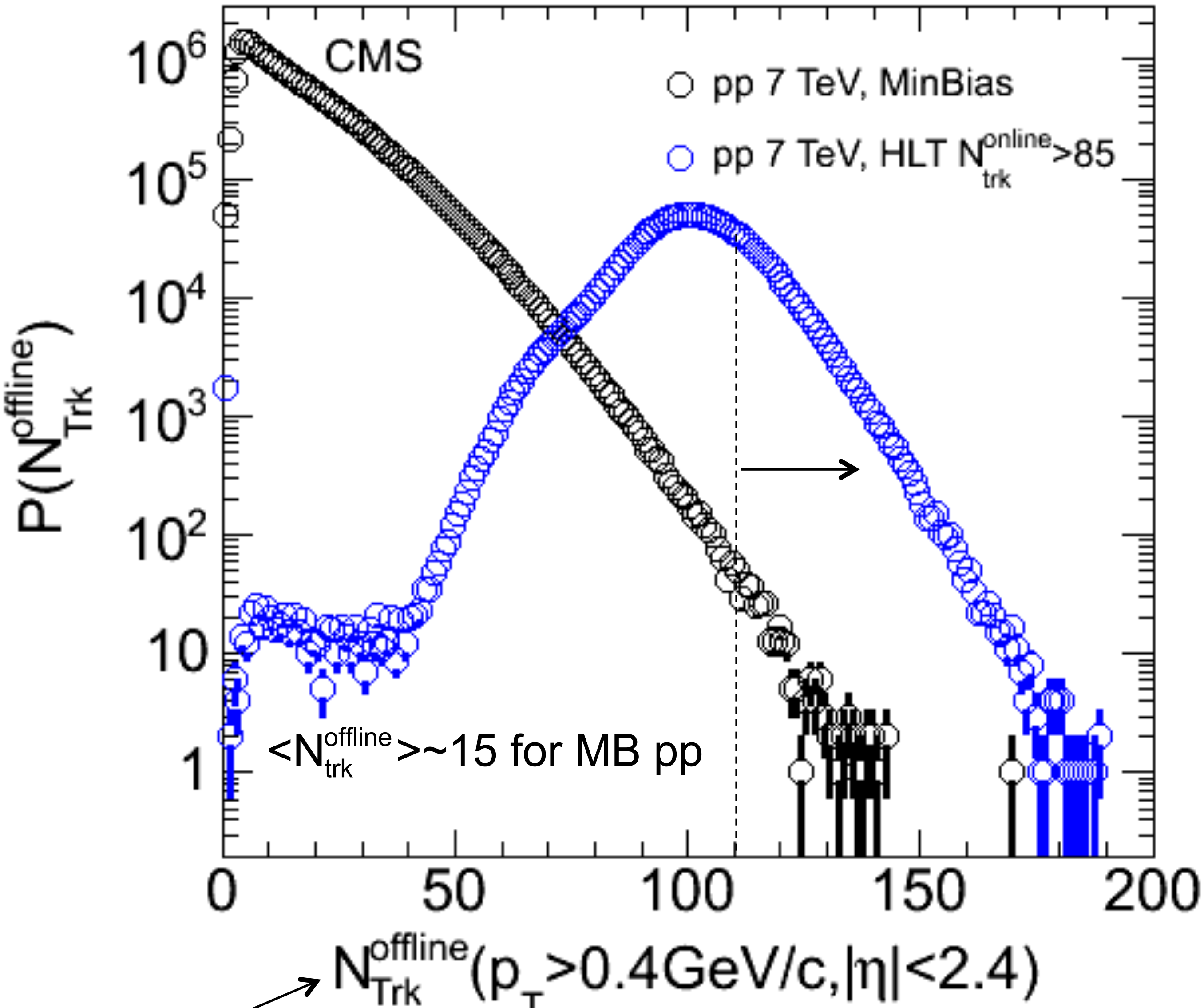
Very high-multiplicity pp events are rare in nature



Raw counts of tracks!

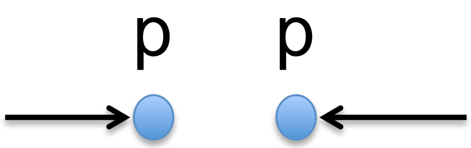
Very high multiplicity pp collisions

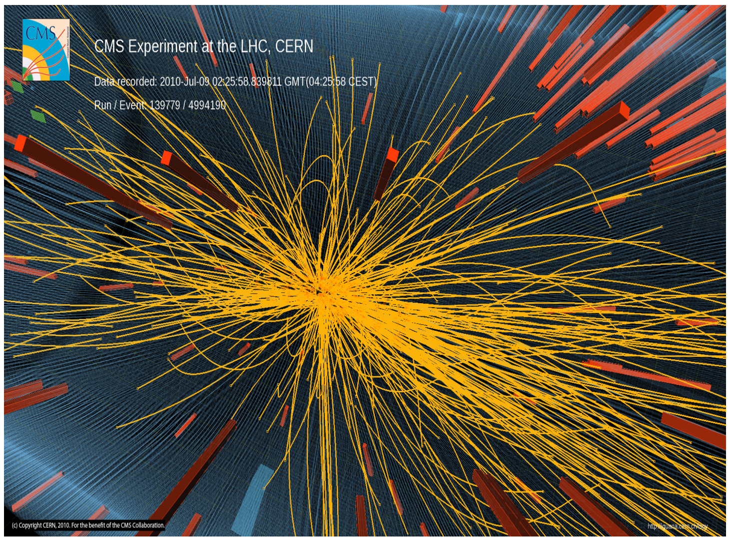
Very high-multiplicity pp events are rare in nature

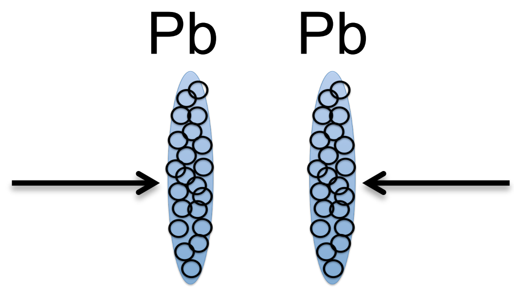


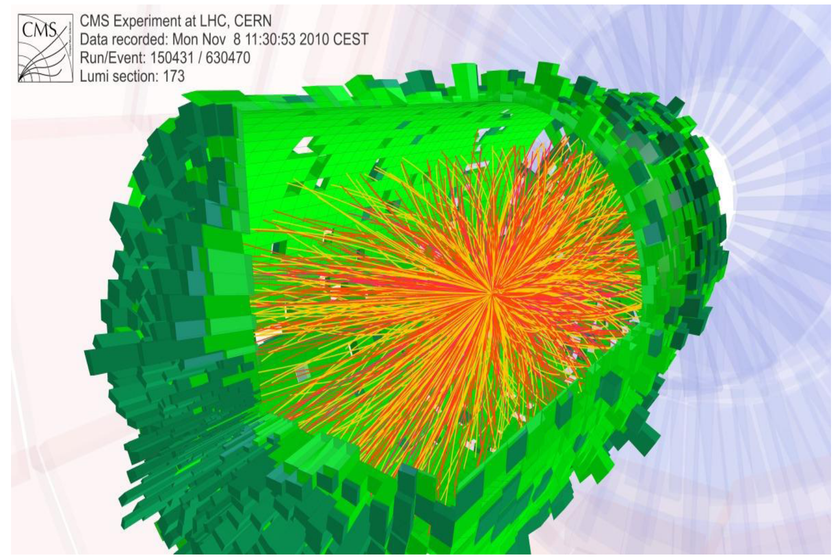
Raw counts of tracks!

High multiplicity in pp and AA



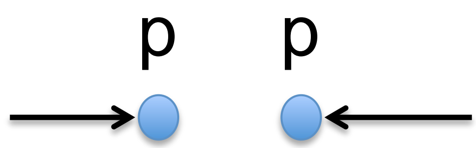


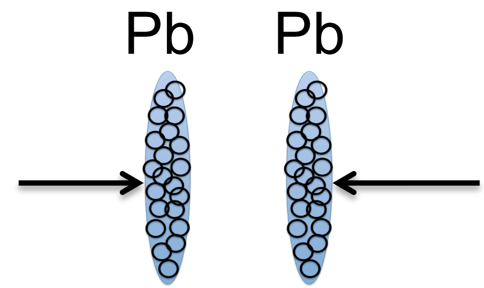


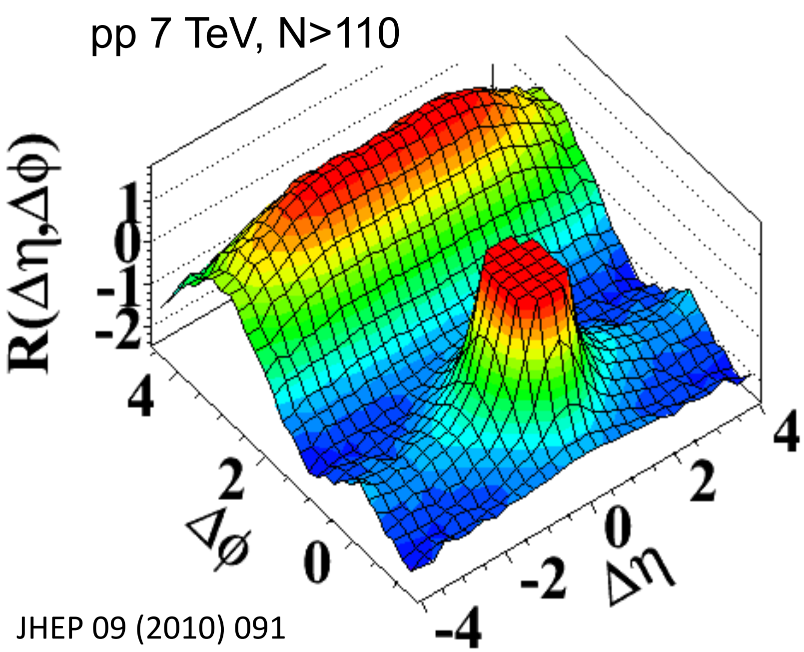


Quark Gluon Plasma (QGP)

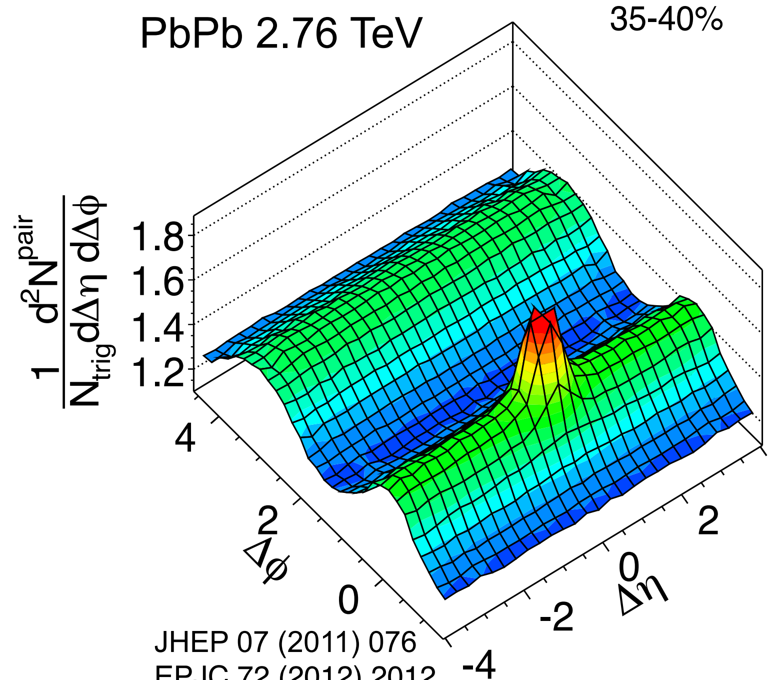
The “ridge” in pp and AA collisions





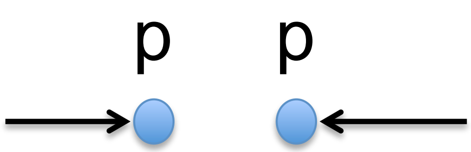


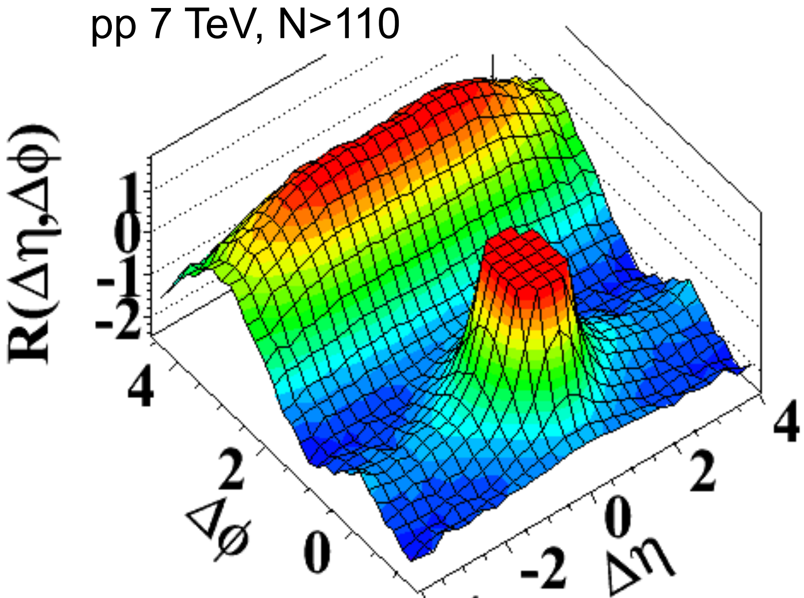
JHEP 09 (2010) 091



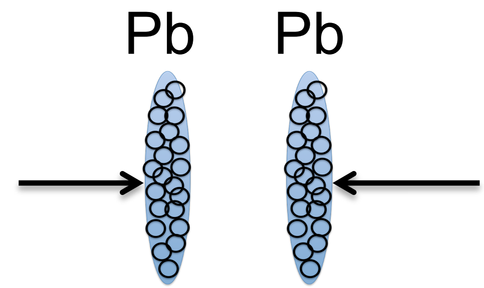
JHEP 07 (2011) 076
EPJC 72 (2012) 2012

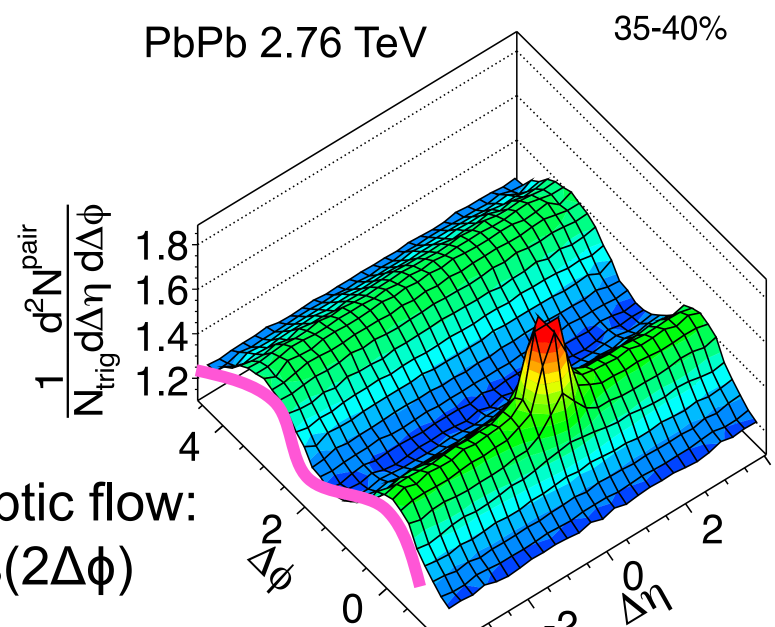
The “ridge” in pp and AA collisions





JHEP 09 (2010) 091

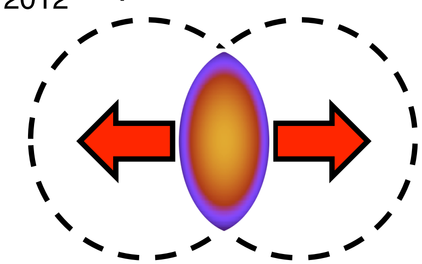




JHEP 07 (2011) 076
EPJC 72 (2012) 2012

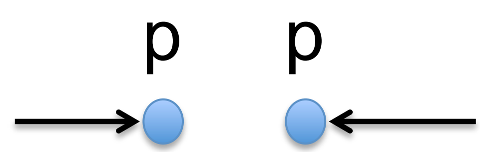
Physical origin of pp ridge is not completely clear

Initial-state geometry
+
collective expansion

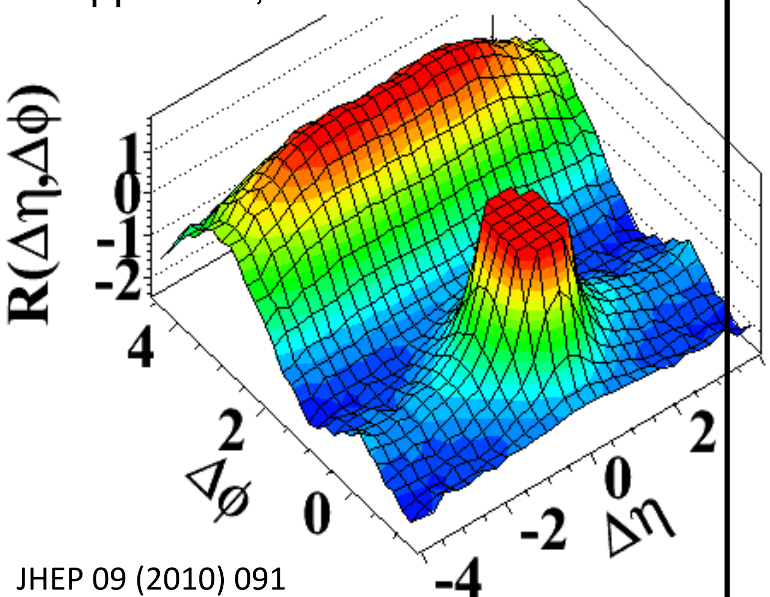


“Smoking gun” of a strongly interacting QGP liquid!

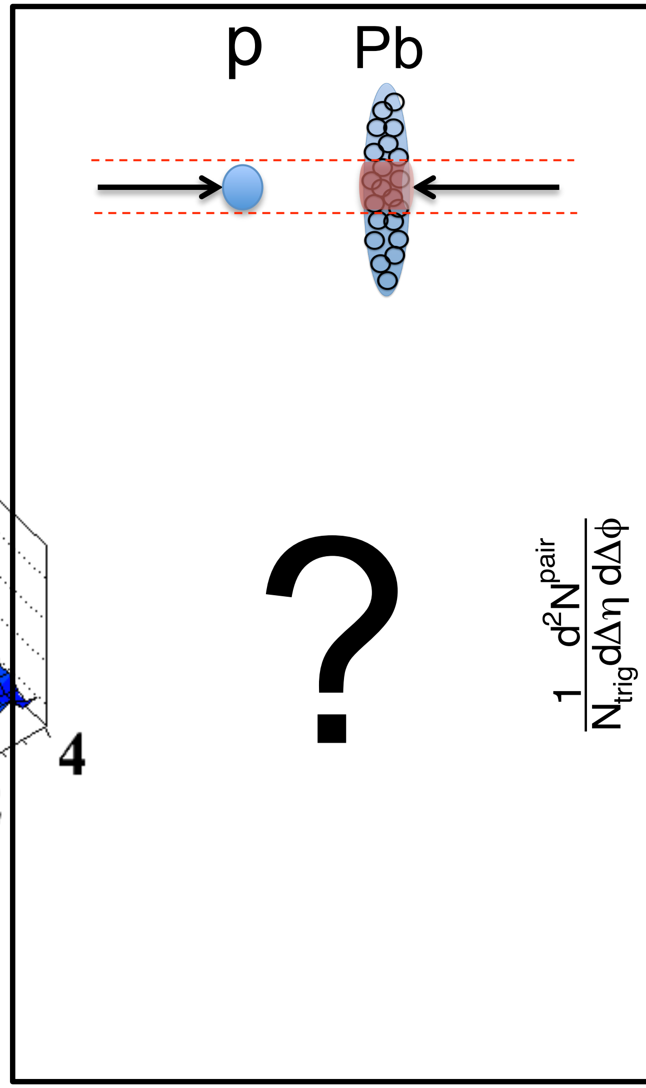
The “ridge” in pA collisions?

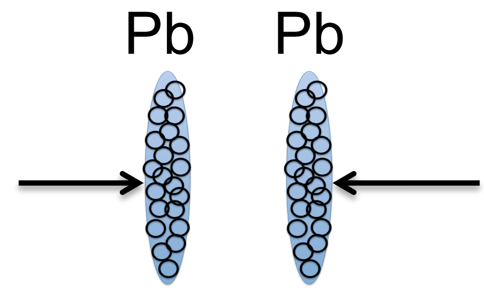


pp 7 TeV, N>110



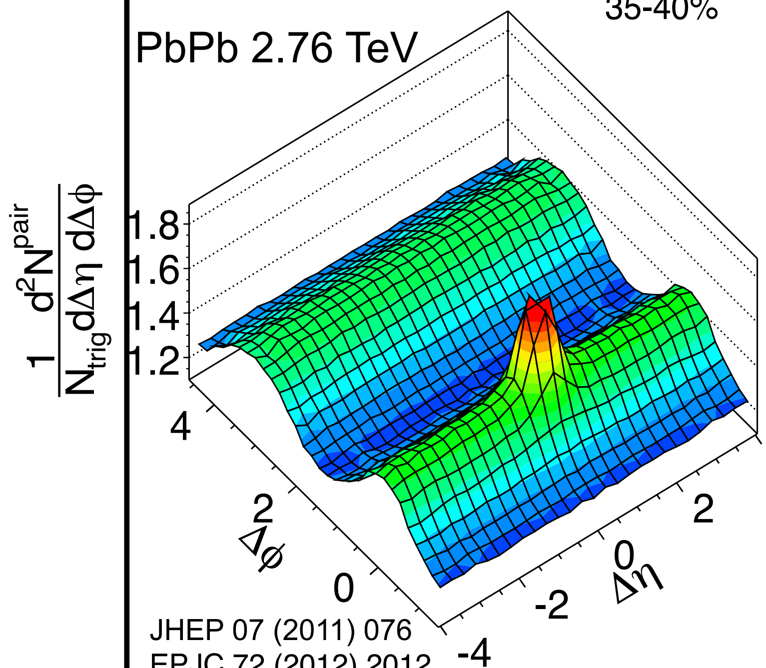
JHEP 09 (2010) 091





PbPb 2.76 TeV

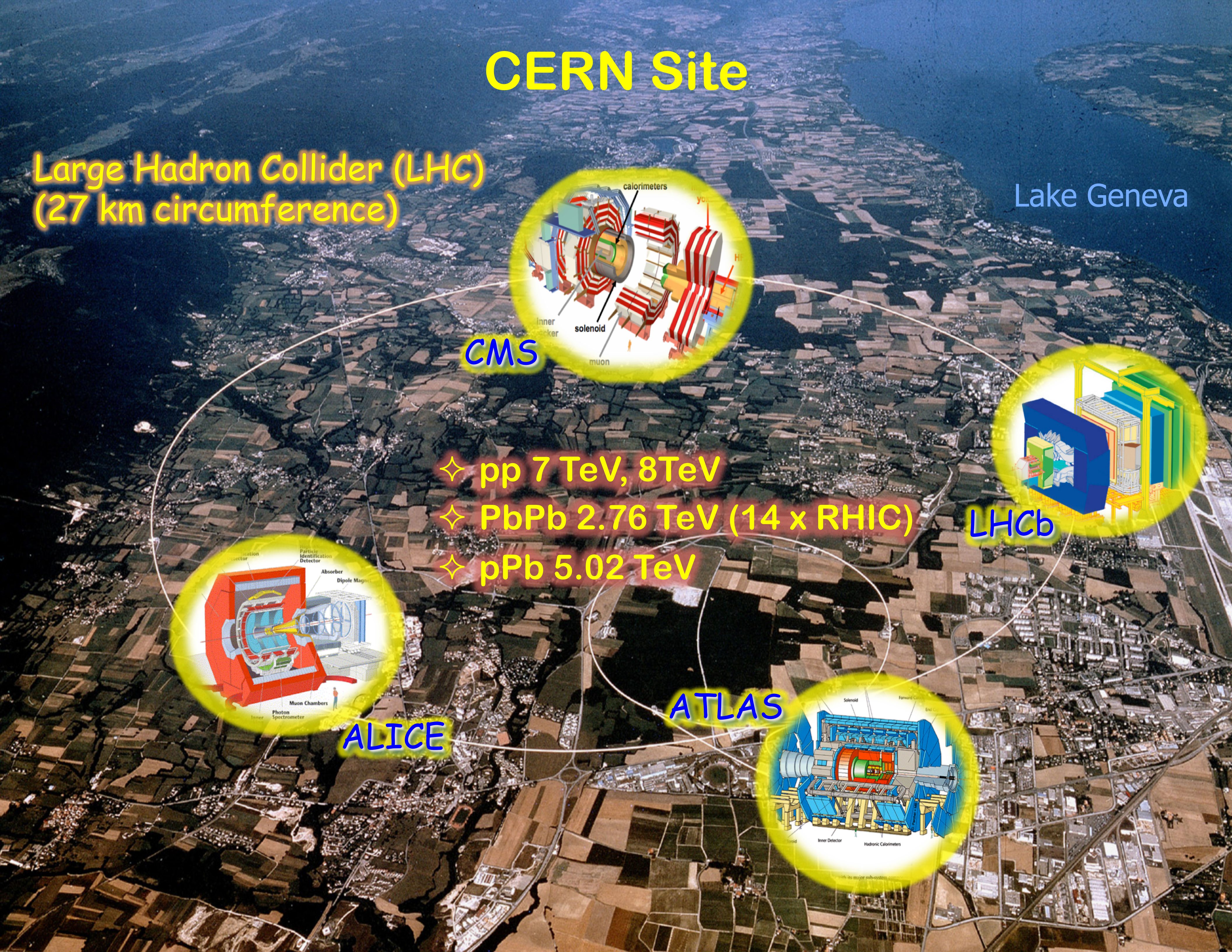
35-40%



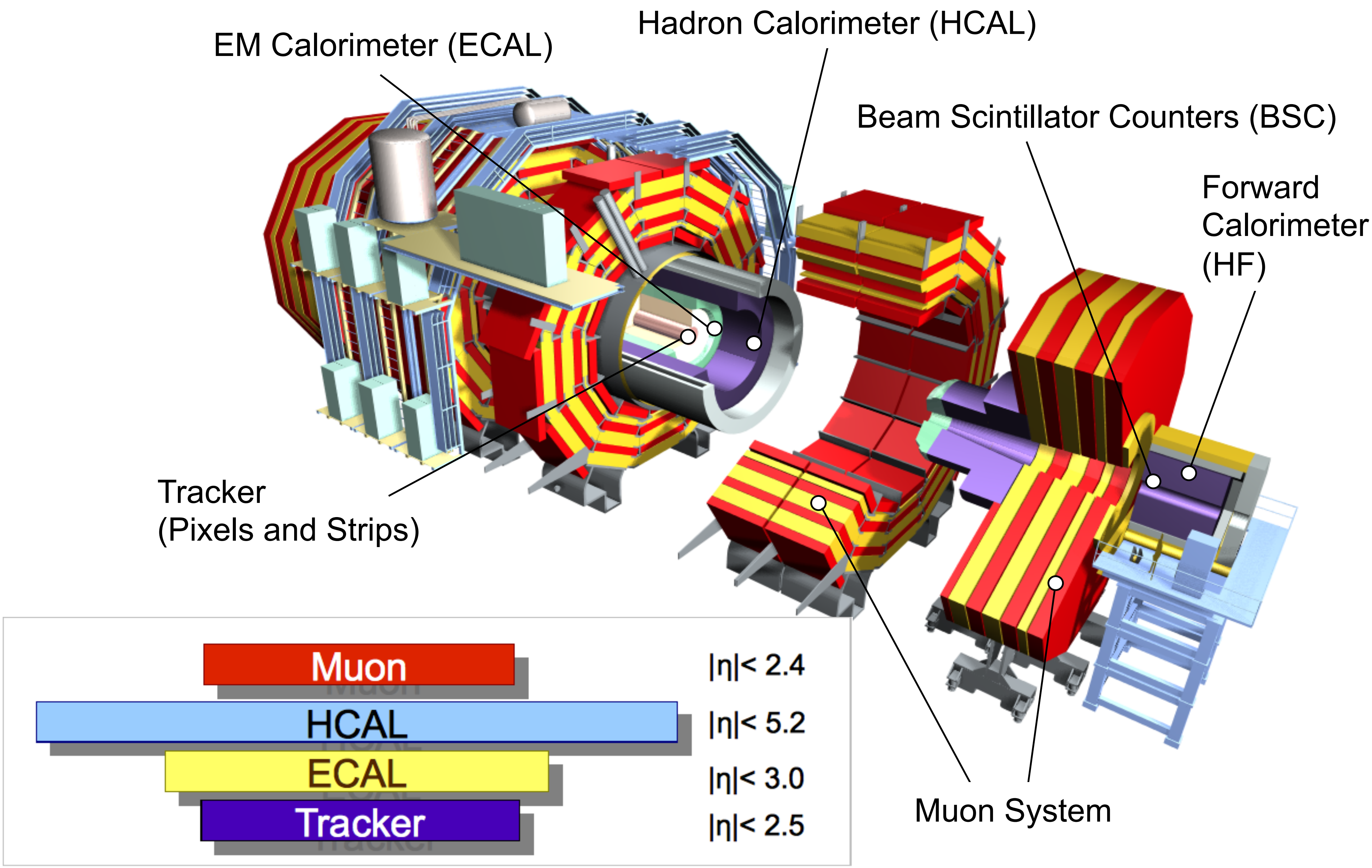
JHEP 07 (2011) 076
EPJC 72 (2012) 2012

What if colliding a proton and a nucleus?

Is there a ridge? how big is it and what makes it?

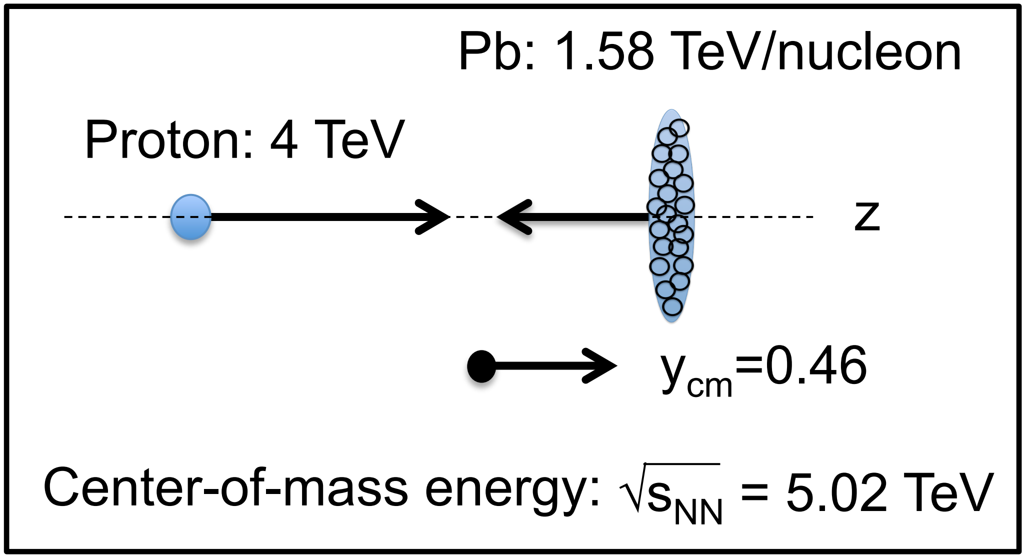

CERN Site
Large Hadron Collider (LHC)
(27 km circumference)
Lake Geneva
calorimeters
solenoid
muon
CMS
LHCb
✧ pp 7 TeV, 8TeV
✧ PbPb 2.76 TeV (14 x RHIC)
✧ pPb 5.02 TeV
Absorber
Muon Chambers
ALICE
ATLAS
Inner Detector
Hadronic Calorimeters

CMS experiment at the LHC



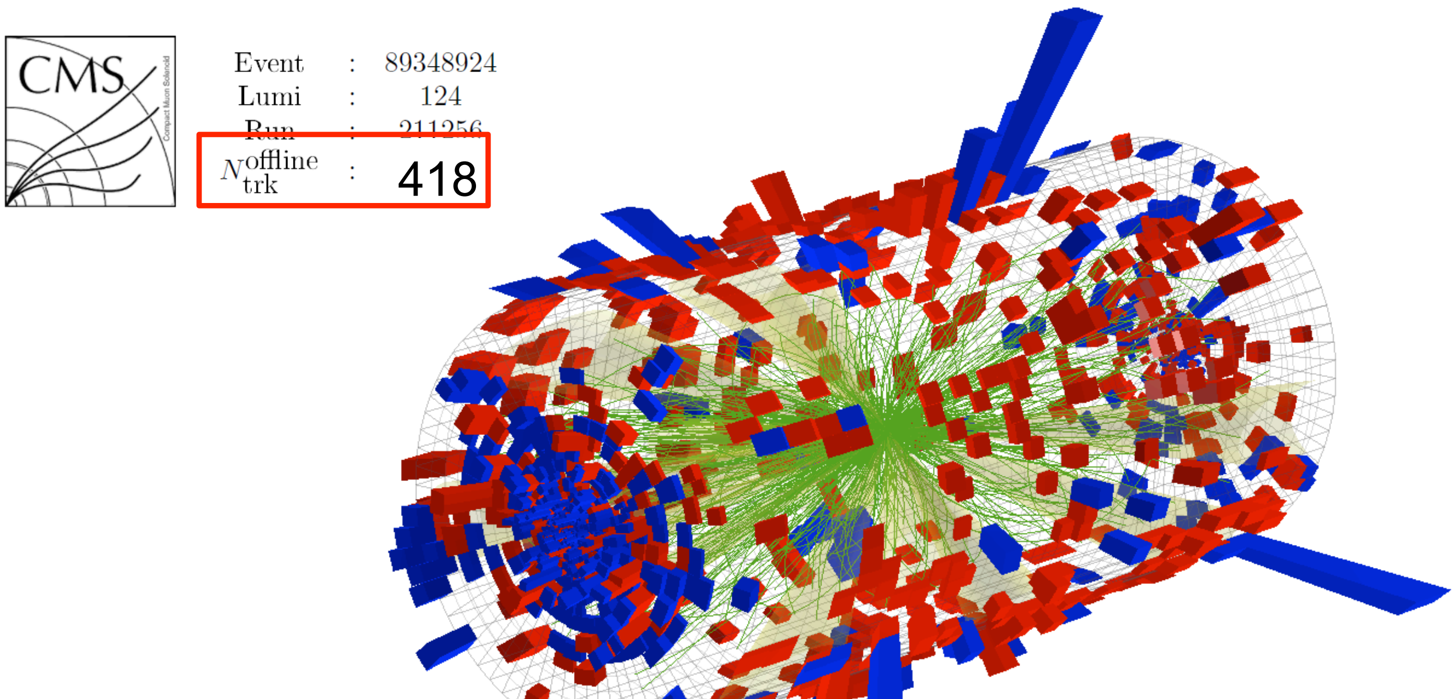
Unprecedented kinematic range and acceptance

Proton-nucleus collisions at the LHC



2012 pilot run (8 hours): 1 μb^{-1}

2013 nominal run (3 weeks): 31 nb^{-1}

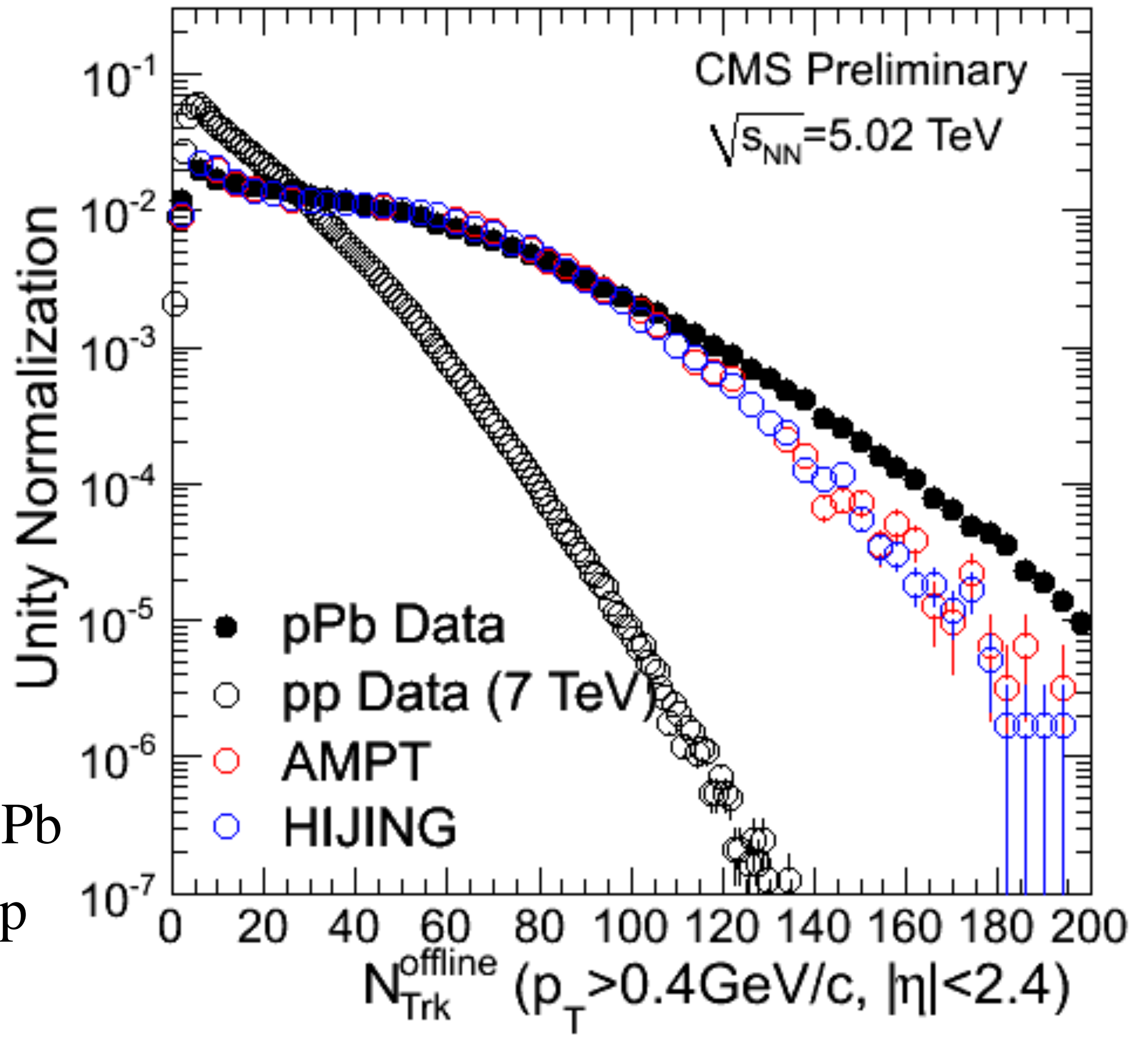


$\langle N_{trk}^{offline} \rangle$~40 for MB pPb

High-multiplicity pPb event

Multiplicity distribution in pPb

2 million minimum bias pPb events from 2012 pilot run



$<N_{trk}^{offline}>$~40 for MB pPb

$<N_{trk}^{offline}>$~15 for MB pp

Much easier to reach high multiplicity in pPb, as expected

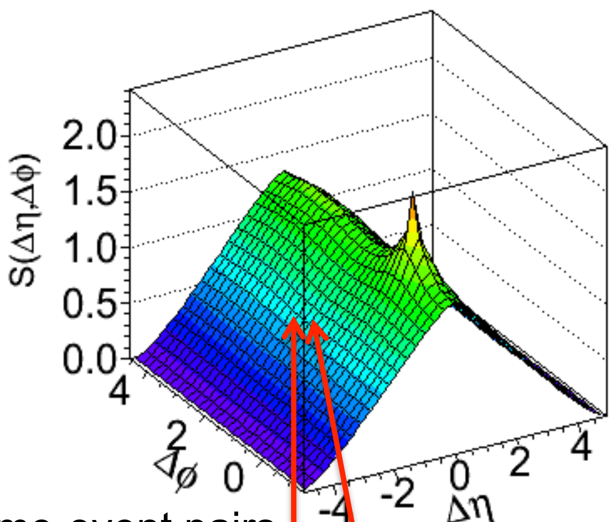
Two-particle correlations at CMS

Pair of two primary reconstructed tracks within $|\eta|<2.4$

- Trigger particle from a p_T^{trig} interval
- Associated particle from a p_T^{assoc} interval

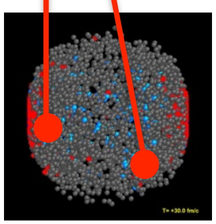
Signal-pair distribution

$$\boxed{S(\Delta\eta,\Delta\varphi) = \frac{1}{N_{trig}} \frac{d^2N^{same}}{d\Delta\eta d\Delta\varphi}}$$



Same-event pairs

Event 1:



$$\boxed{\begin{aligned}\Delta\eta &= \eta^{assoc} - \eta^{trig}\\ \Delta\phi &= \phi^{assoc} - \phi^{trig}\end{aligned}}$$

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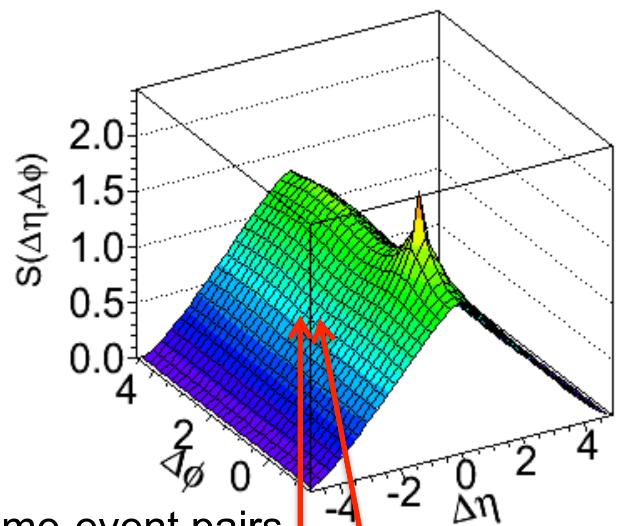

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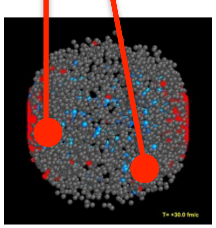
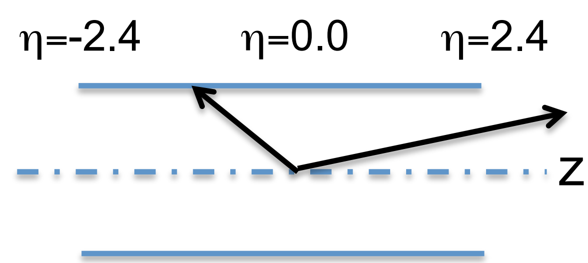


Triangular shape in Δη due to limited acceptance



$$\boxed{\begin{aligned}\Delta\eta &= \eta^{assoc} - \eta^{trig}\\ \Delta\phi &= \phi^{assoc} - \phi^{trig}\end{aligned}}$$

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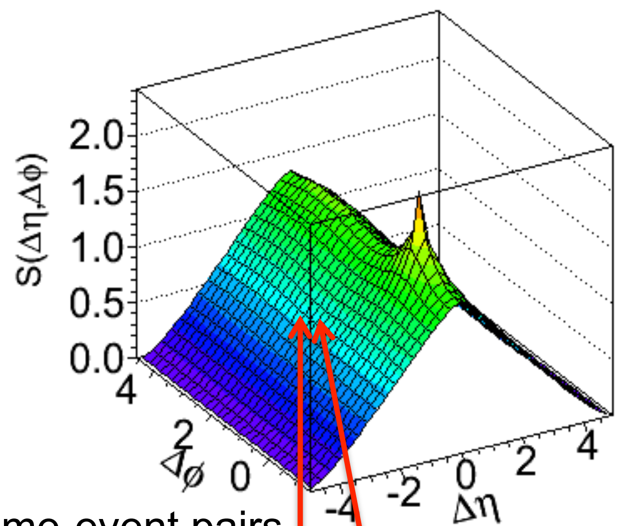
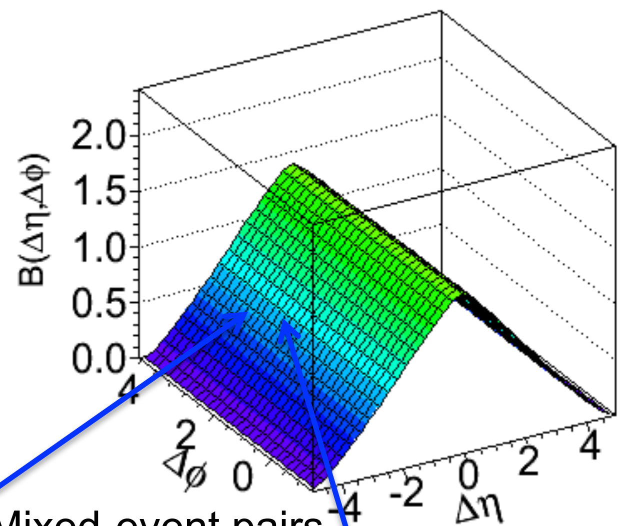


Same-event pairs

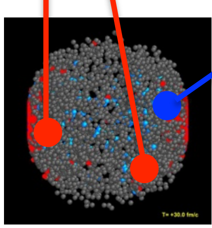
Background-pair distribution

$$B(\Delta\eta,\Delta\varphi) = \frac{1}{N_{trig}} \frac{d^2N^{mix}}{d\Delta\eta d\Delta\varphi}$$

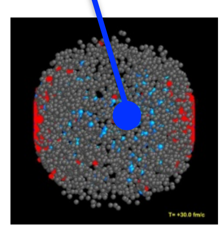


Mixed-event pairs (similar z_{vtx})

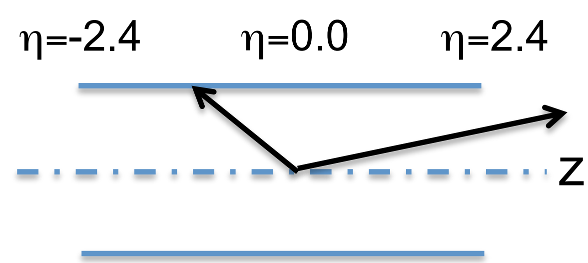
Event 1:



Event 2:



Triangular shape in $\Delta\eta$ due to limited acceptance



$$\Delta\eta = \eta^{assoc} - \eta^{trig}$$
$$\Delta\phi = \phi^{assoc} - \phi^{trig}$$

Two-particle correlations at CMS

Pair of two primary reconstructed tracks within |η|<2.4

- Trigger particle from a p_T^{trig} interval
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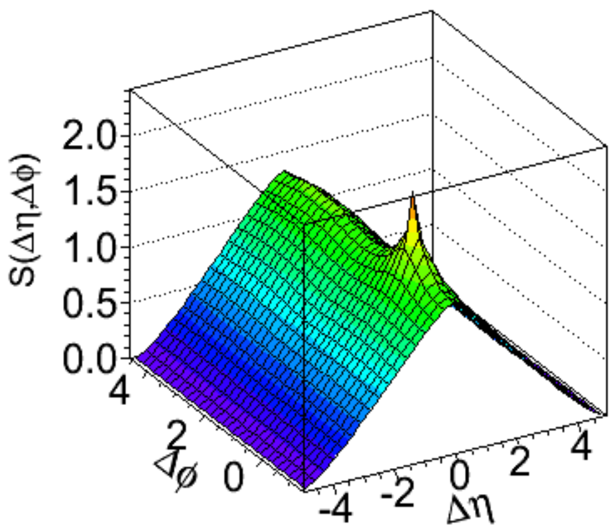
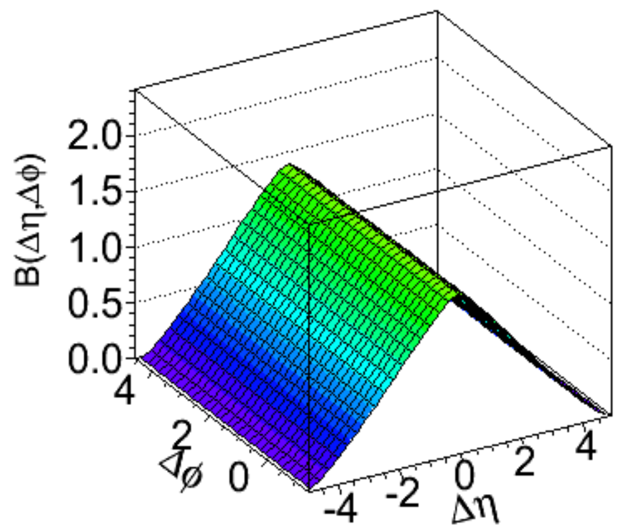
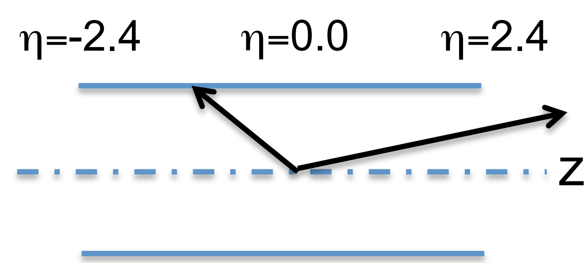


Background-pair distribution

$$B(\Delta\eta,\Delta\varphi) = \frac{1}{N_{trig}} \frac{d^2N^{mix}}{d\Delta\eta d\Delta\varphi}$$



Triangular shape in Δη due to limited acceptance

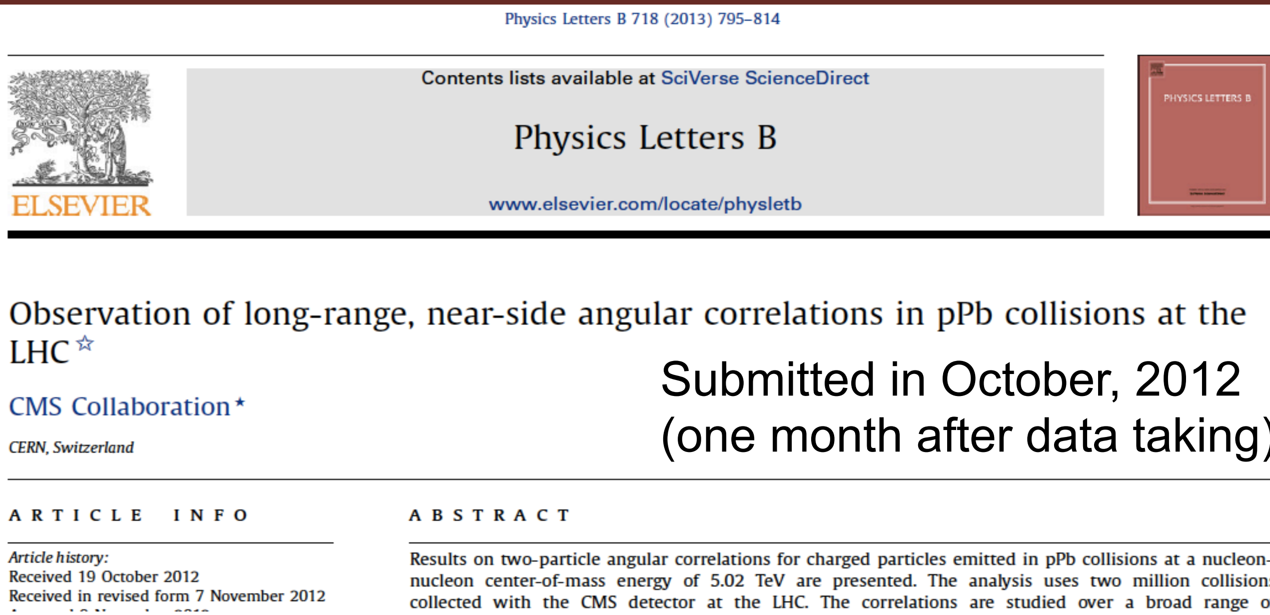


Pair yield per trigger particle:

$$\frac{1}{N_{trg}} \frac{d^2N}{d\Delta\eta d\Delta\phi} = B(0,0) \times \frac{S(\Delta\eta,\Delta\phi)}{B(\Delta\eta,\Delta\phi)}$$

$$\Delta\eta = \eta^{assoc} - \eta^{trig}$$
$$\Delta\phi = \phi^{assoc} - \phi^{trig}$$

First correlation result from pPb pilot run


Physics Letters B 718 (2013) 795–814

Contents lists available at SciVerse ScienceDirect

Physics Letters B

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Observation of long-range, near-side angular correlations in pPb collisions at the LHC ☆

CMS Collaboration *

CERN, Switzerland

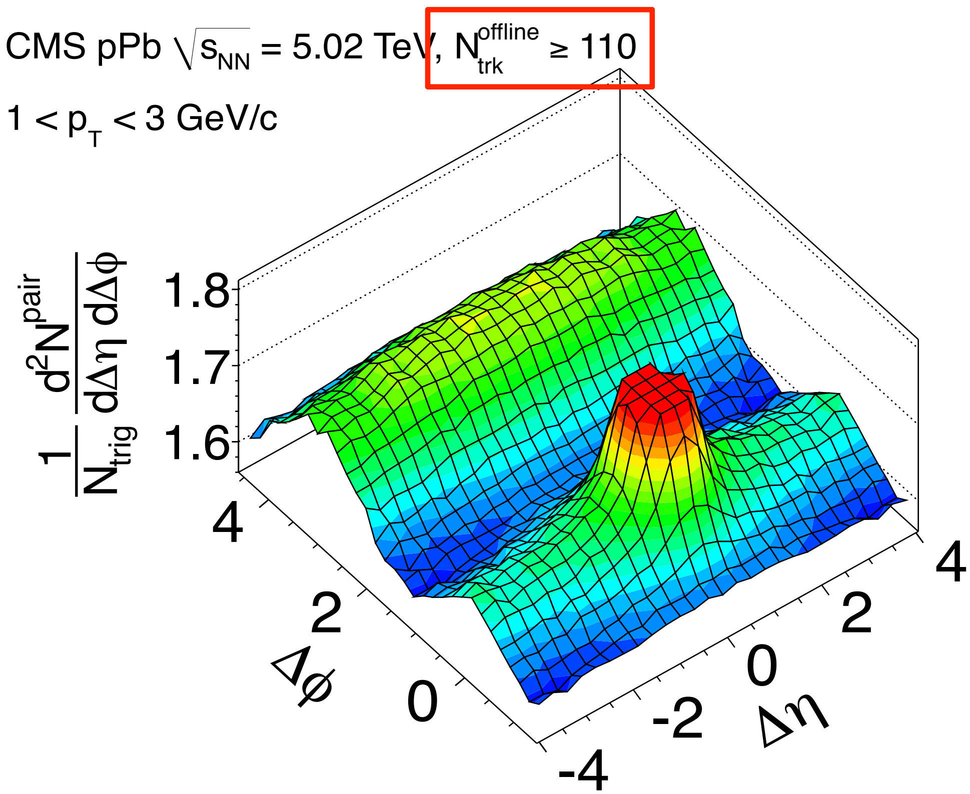
ARTICLE INFO

Article history:
Received 19 October 2012
Received in revised form 7 November 2012

ABSTRACT

Results on two-particle angular correlations for charged particles emitted in pPb collisions at a nucleon–nucleon center-of-mass energy of 5.02 TeV are presented. The analysis uses two million collisions collected with the CMS detector at the LHC. The correlations are studied over a broad range of

Submitted in October, 2012
(one month after data taking)



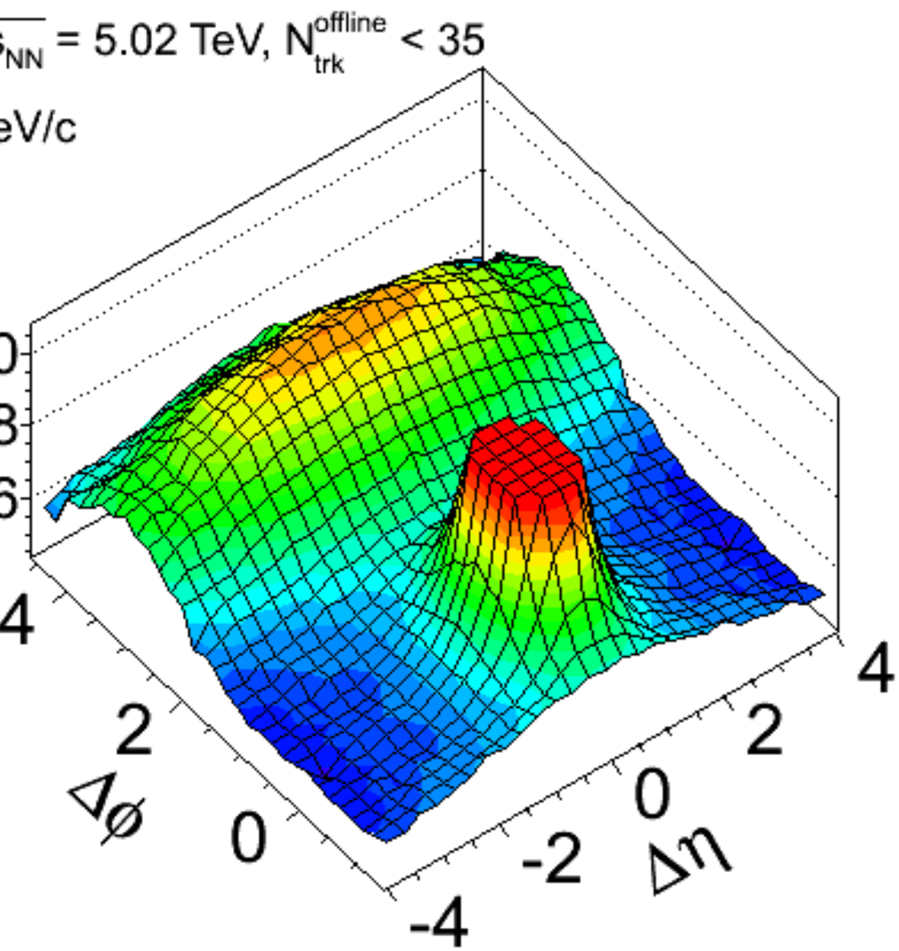
Yes, there is a ridge in pA!!!

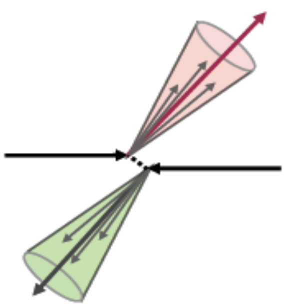
Much more significant than in pp!

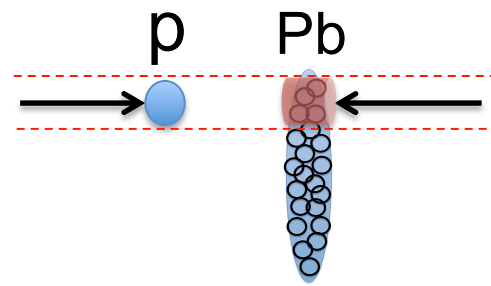
Confirmed later by ALICE and ATLAS

First correlation result from pPb pilot run

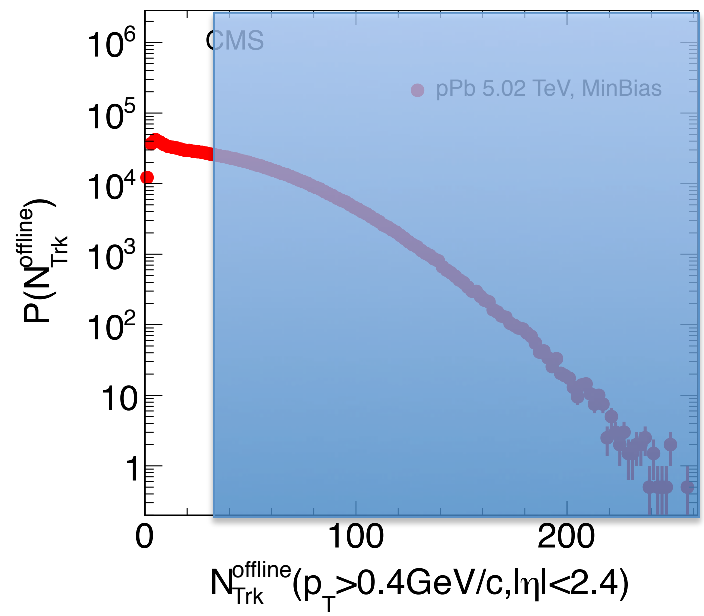
$N_{trk}^{offline} < 35$







2 million events total

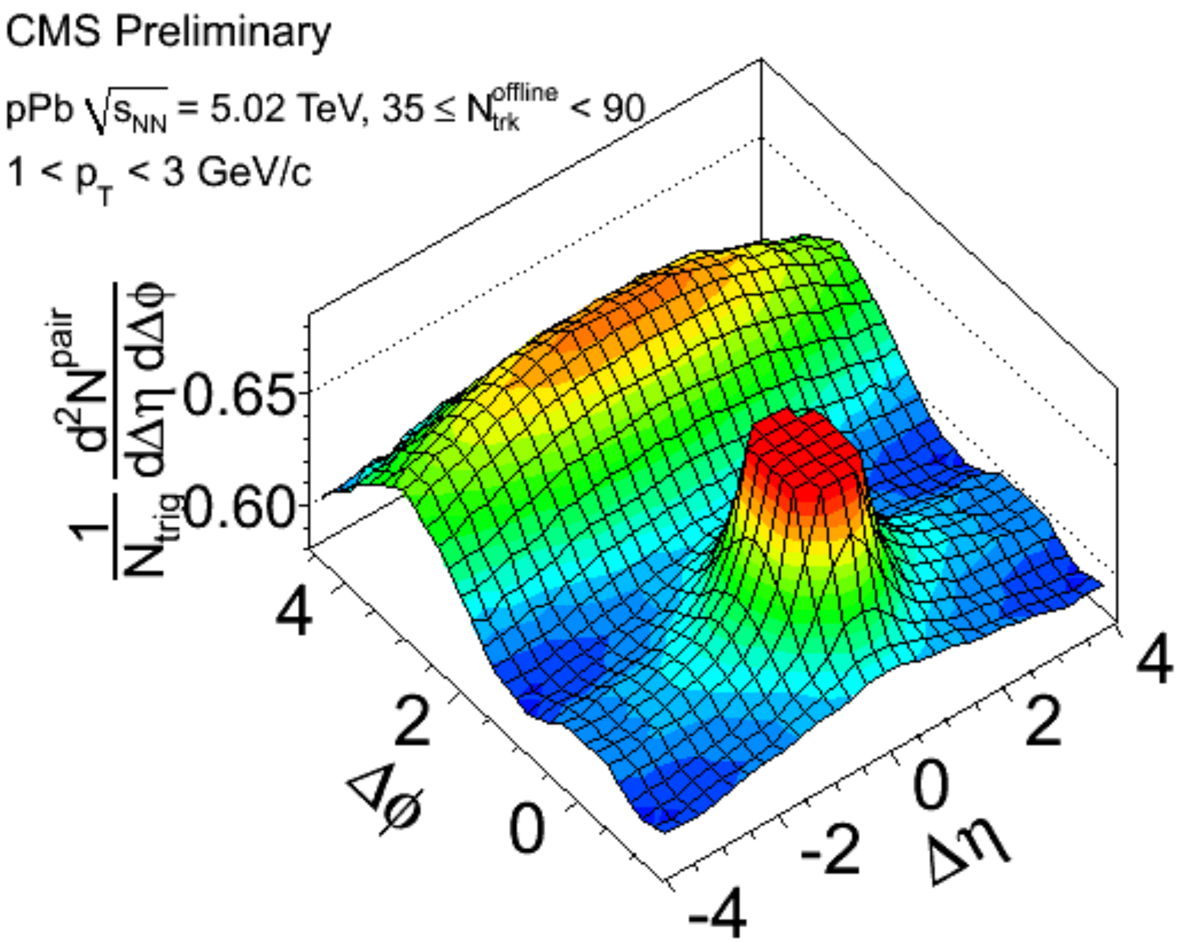


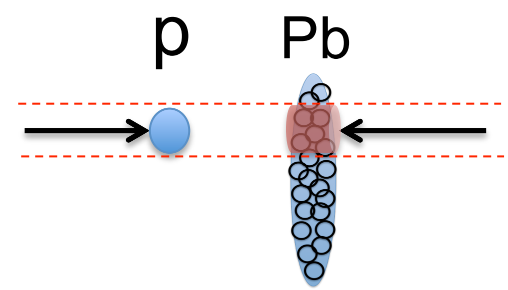
Fraction of cross section: 50.4%

Dijet-like correlations in low multiplicity (or peripheral) pPb!

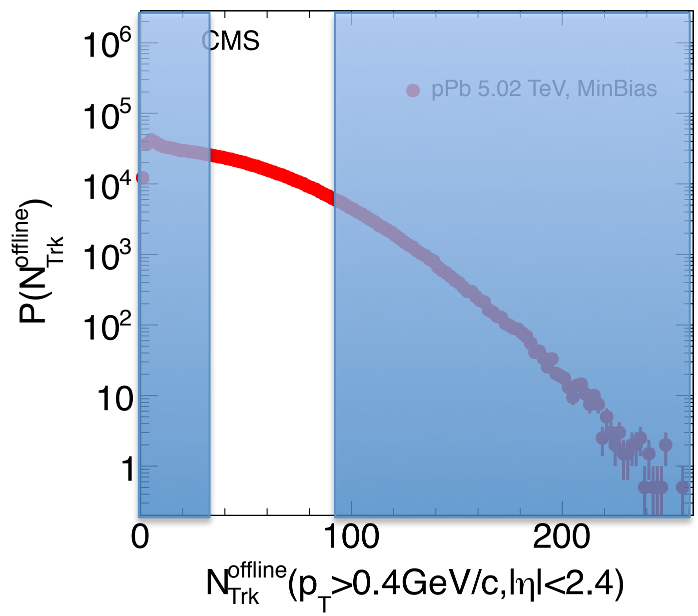
First correlation result from pPb pilot run

$35 \leq N_{trk}^{offline} < 90$





2 million events total

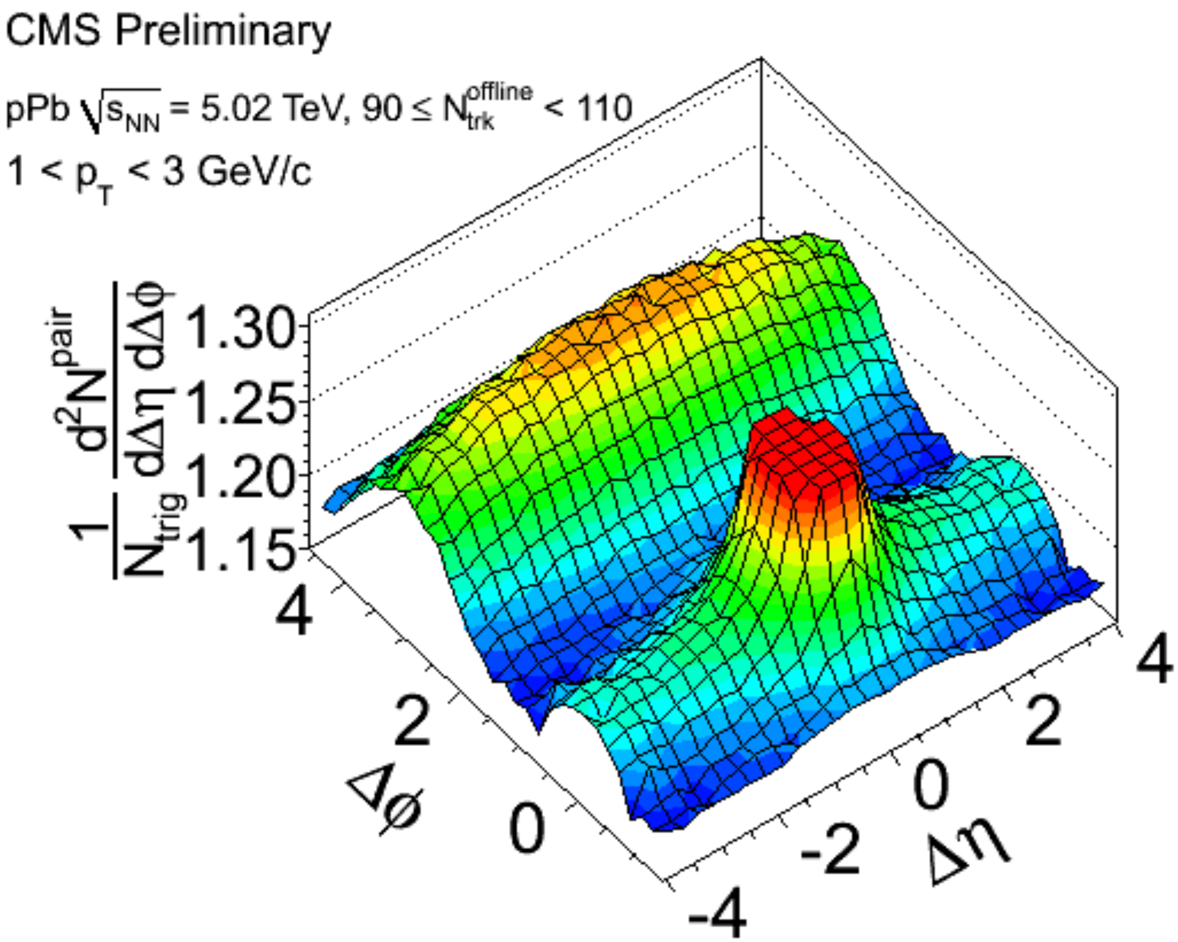


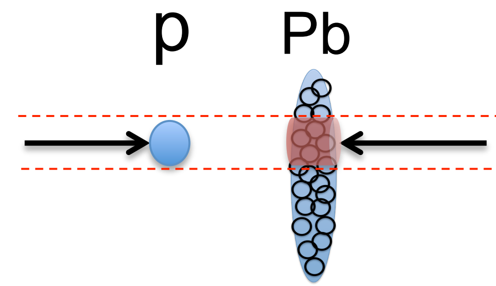
Fraction of cross section: 41.9%

Ridge on the near side (Δϕ~0) turns on as multiplicity increases

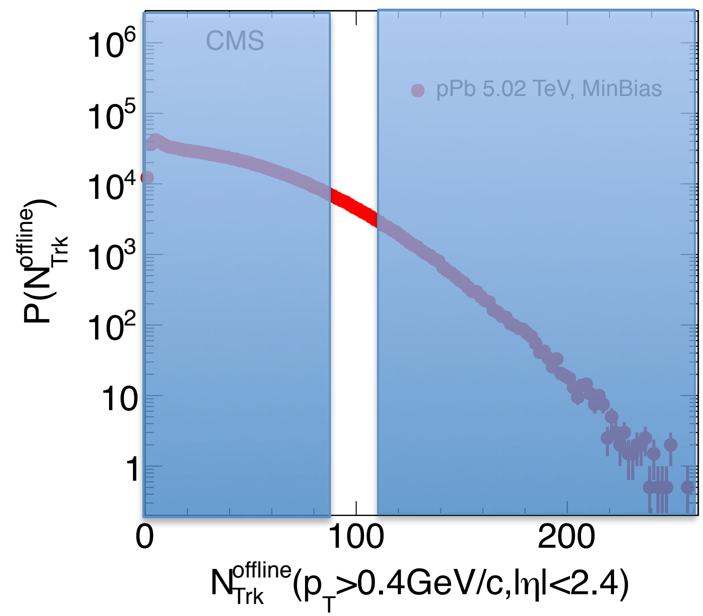
First correlation result from pPb pilot run

$90 \leq N_{trk}^{offline} < 110$





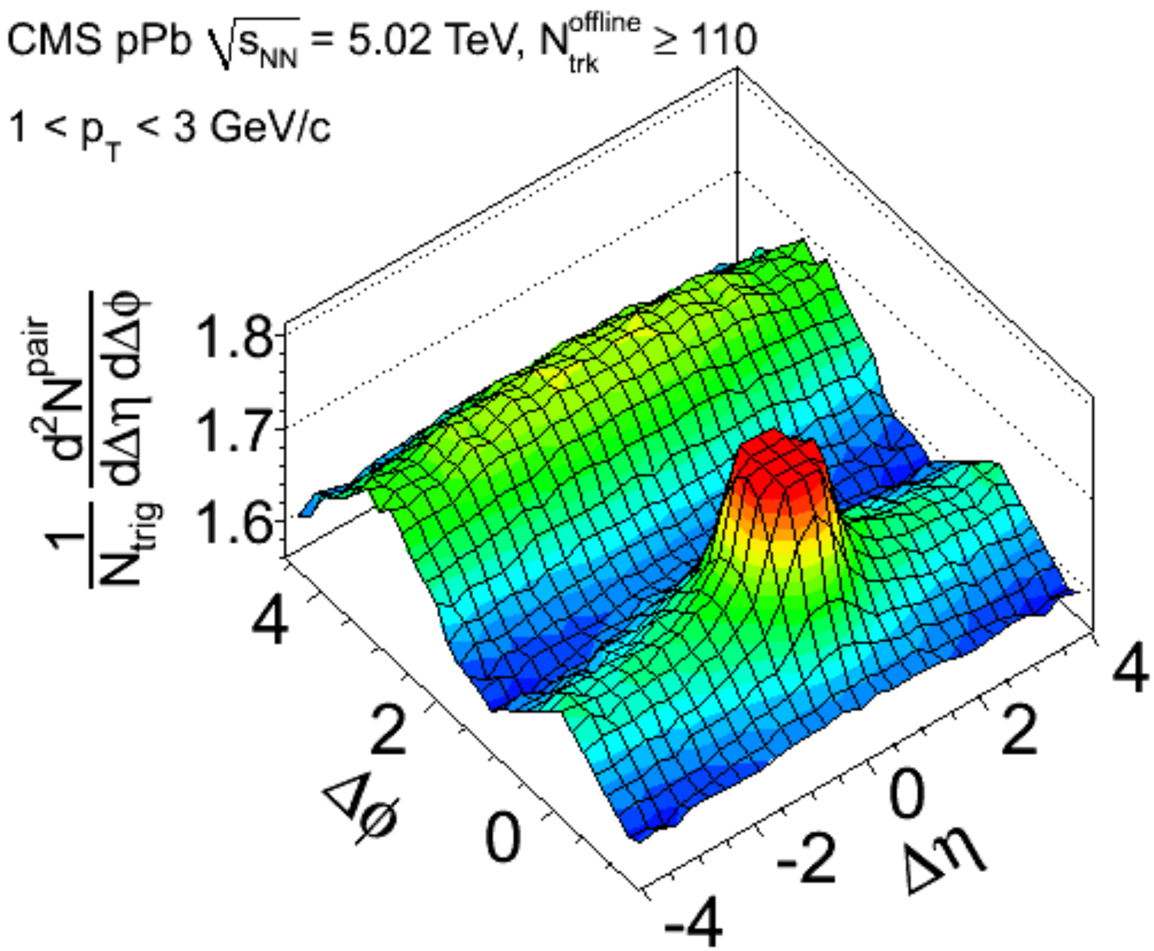
2 million events total

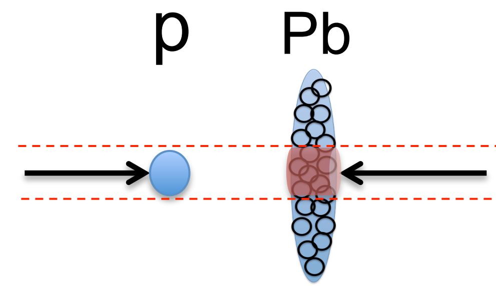


Fraction of cross section: 4.6%

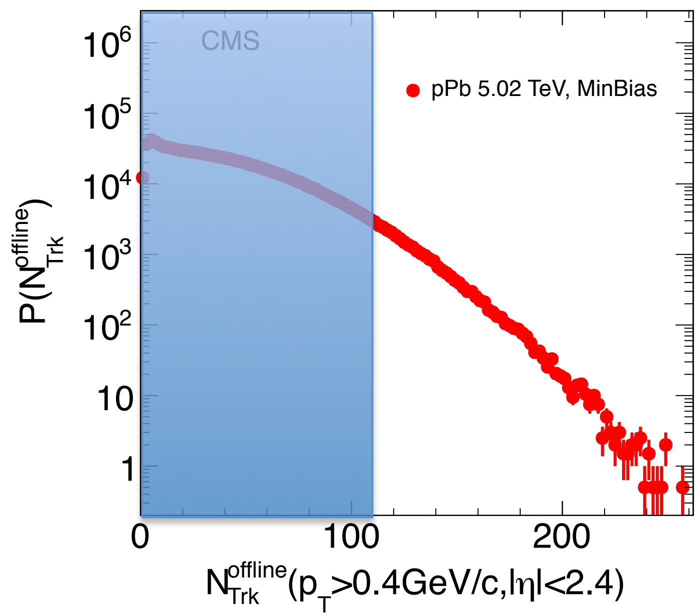
First correlation result from pPb pilot run

$N_{trk}^{offline} \geq 110$



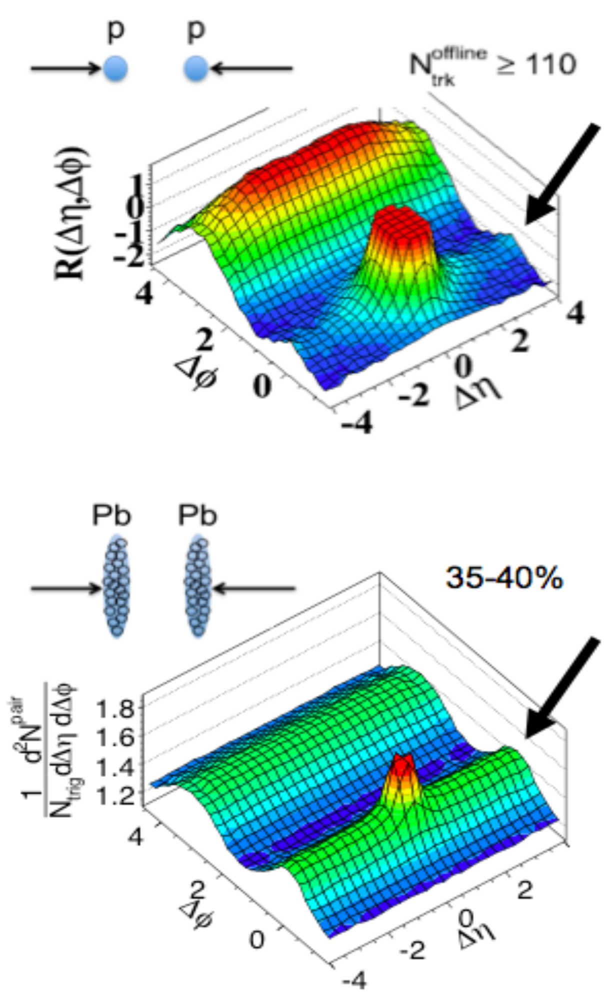


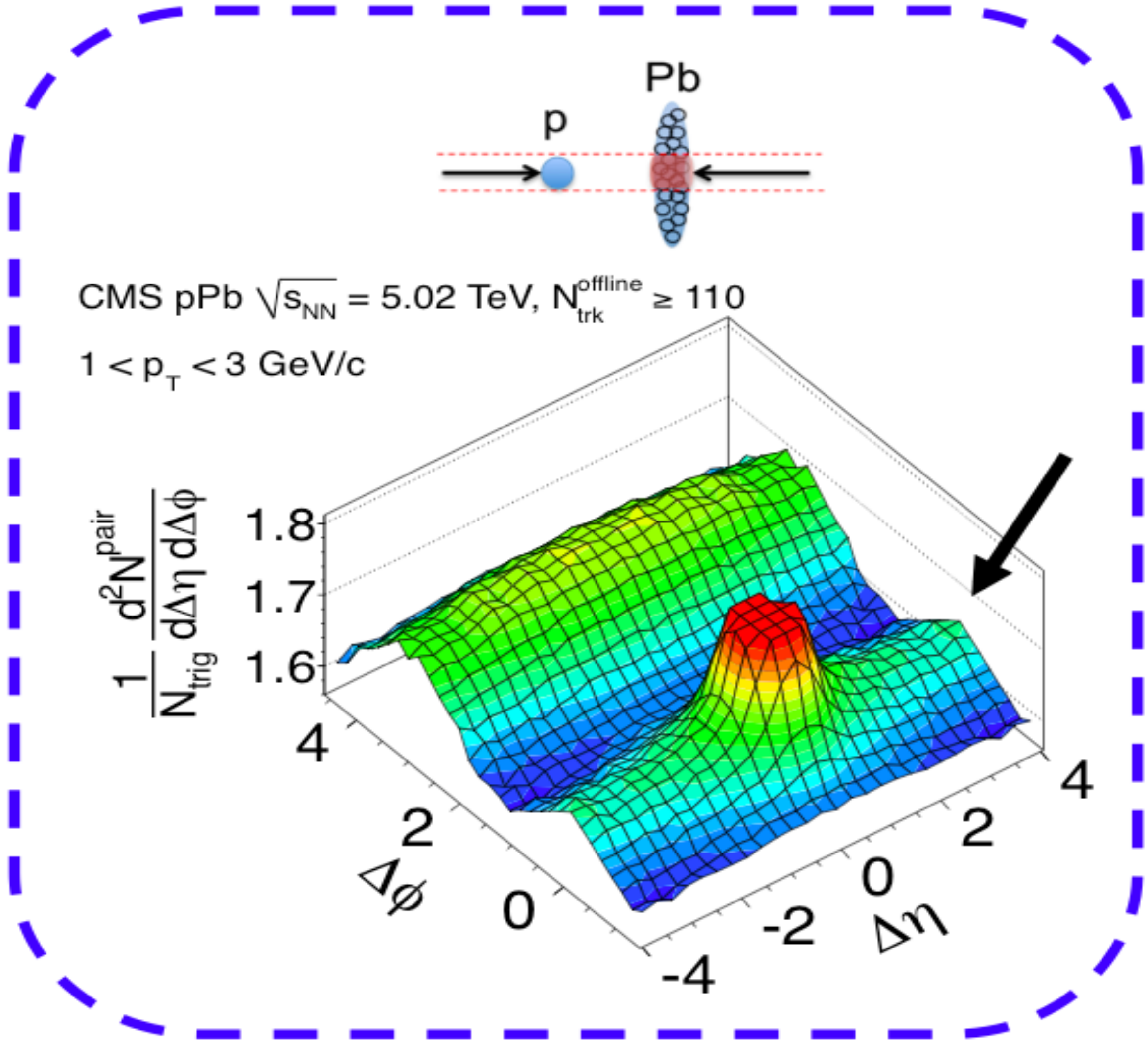
2 million events total



Fraction of cross section: 3.1%

A complete picture of ridge correlations





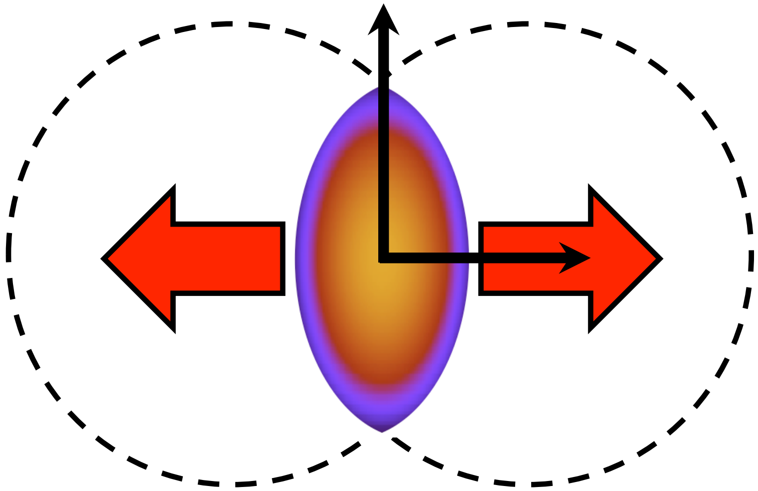
Is there a common origin of the ridge in all systems?

- Flow-like effect similar to PbPb? Final-state effect seen in pPb?
- Other QCD mechanisms in smaller systems?

Initial-state eccentricity:

$$\varepsilon_{std} = \frac{\sigma_y^2 - \sigma_x^2}{\sigma_y^2 + \sigma_x^2}$$

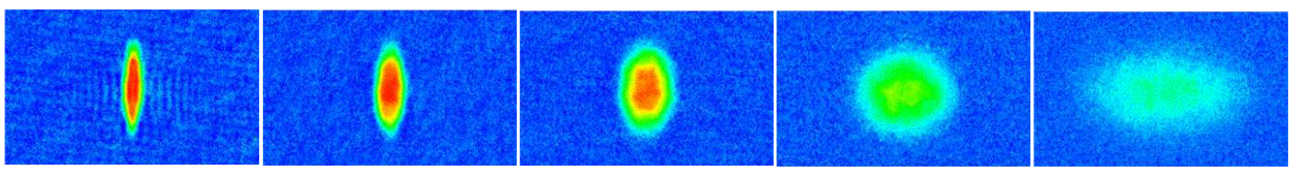
Small pressure gradient



Large pressure gradient

Strongly interacting system like a liquid

Time ⟶

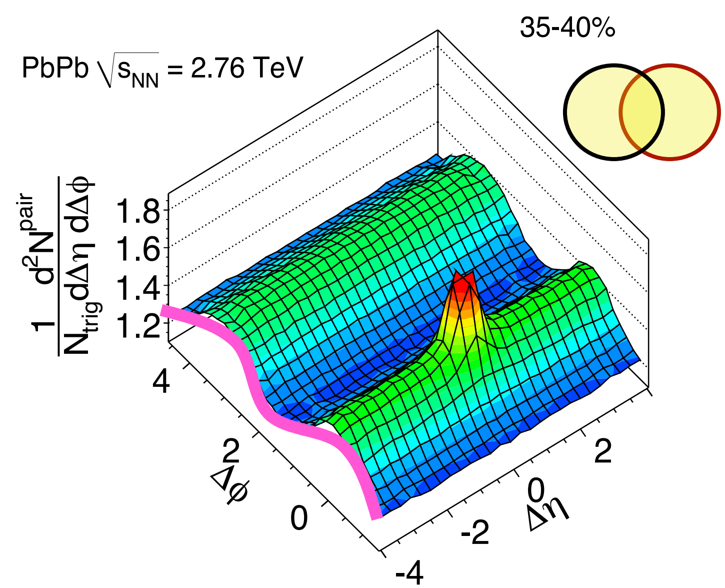


J. Thomas

n.b. picture shows expansion of ultracold atoms released from trap

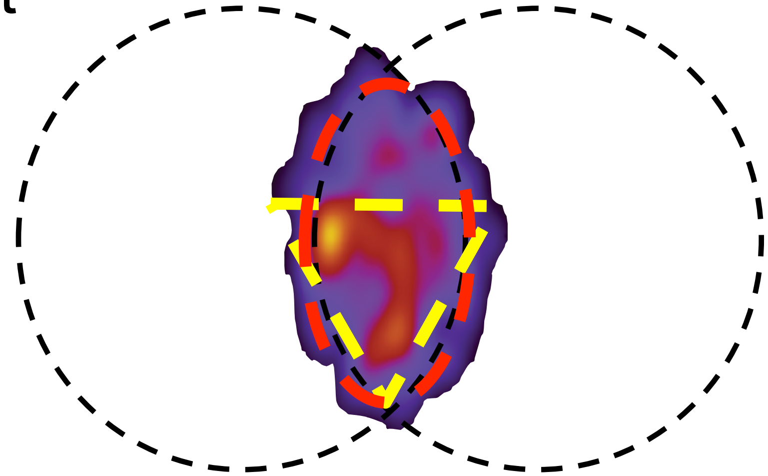
$$\frac{1}{N_{trig}} \frac{dN^{pair}}{d\Delta\phi} \sim 1 + 2(v_2)^2 \cos(2\Delta\phi)$$

elliptic flow

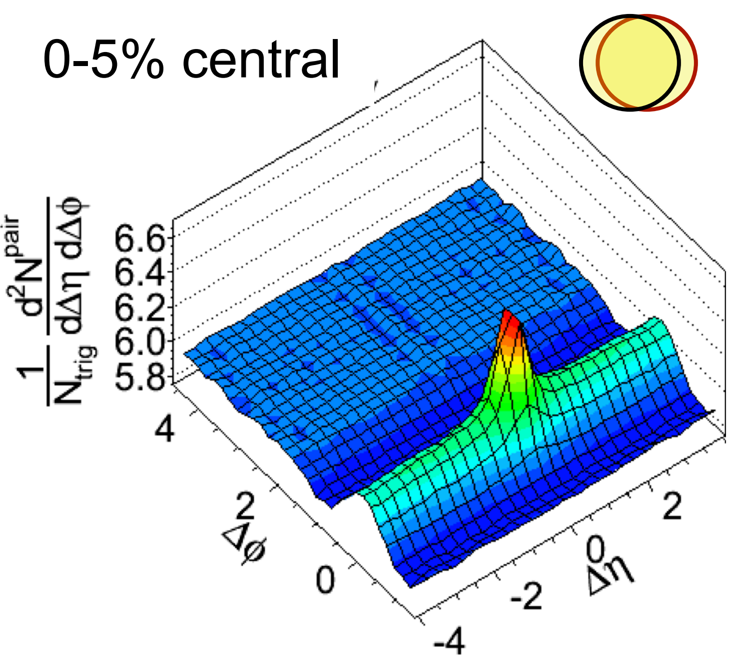


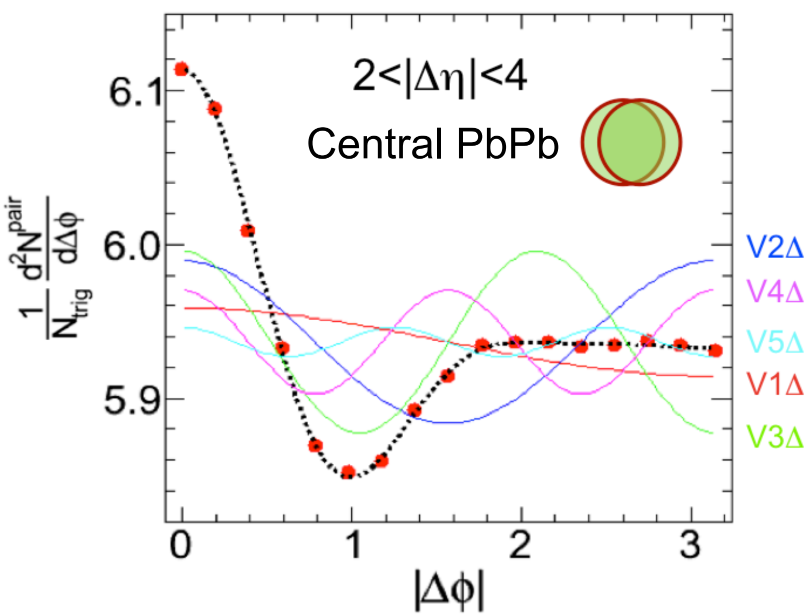
Hydrodynamic flow in AA

Real event-by-event collision geometry:

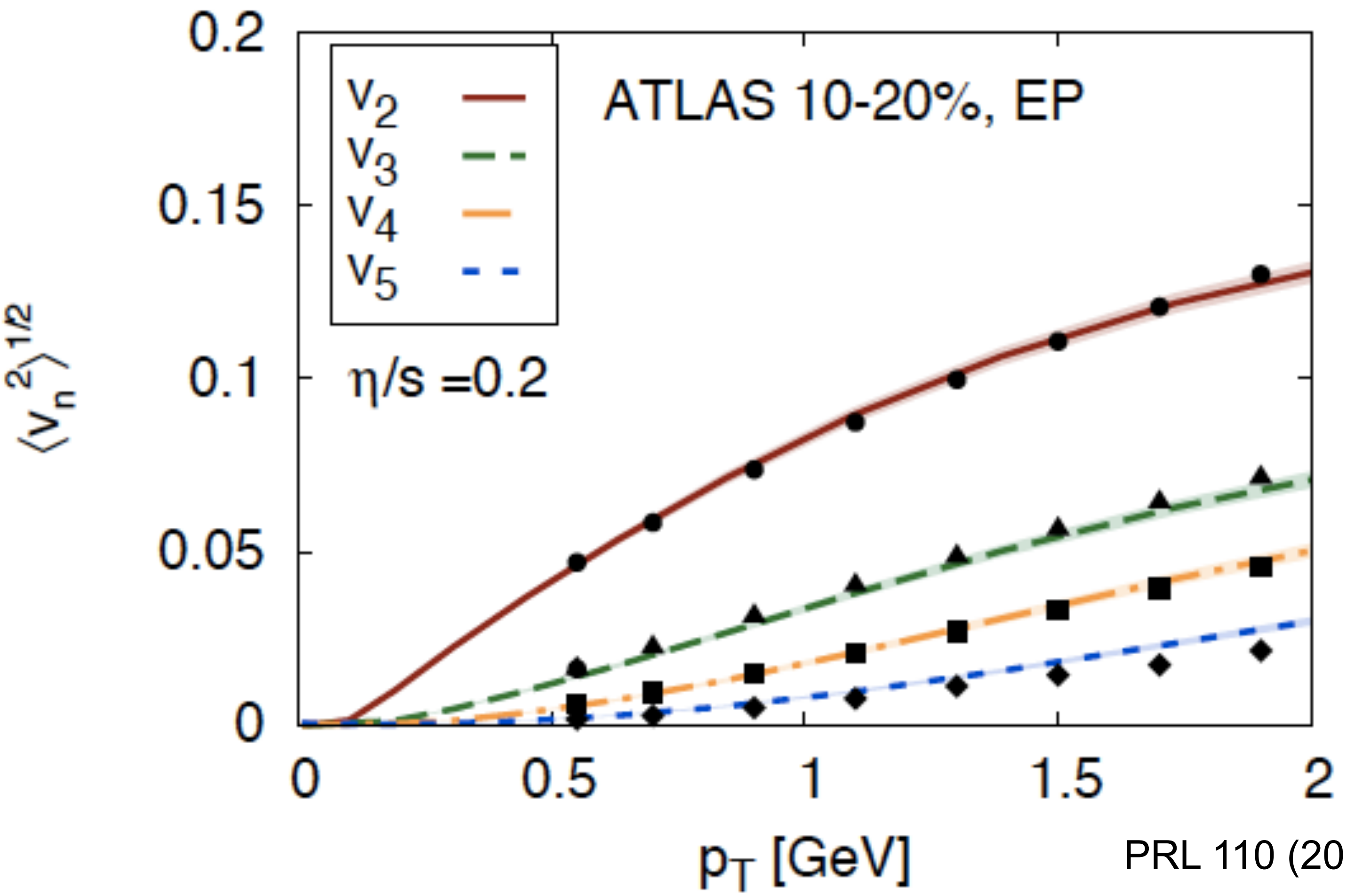


$$\frac{1}{N_{trig}}\frac{dN^{pair}}{d\Delta\phi} \sim 1 + 2(v_2)^2\cos(2\Delta\phi) + 2(v_3)^2\cos(3\Delta\phi) + 2(v_4)^2\cos(4\Delta\phi) + 2(v_5)^2\cos(5\Delta\phi)$$





Hydrodynamic flow in AA



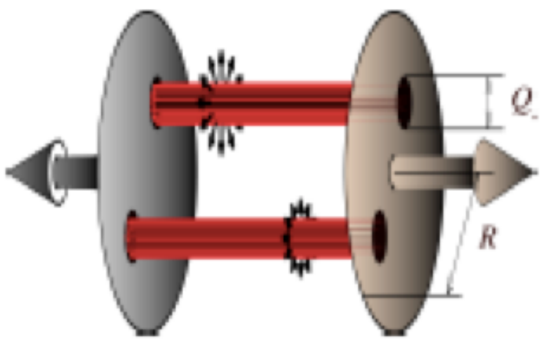
PRL 110 (2013) 012302

Hydro faithfully transposes this shape into final-state particle azimuthal correlations

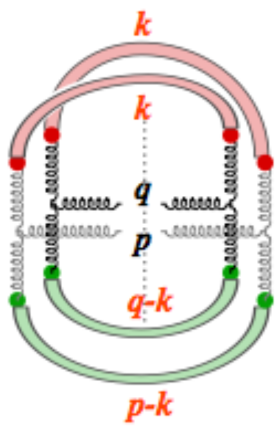
Ridge from Color Glass Condensate

Ridge in pp and pA from initial gluon saturation ("predicted")

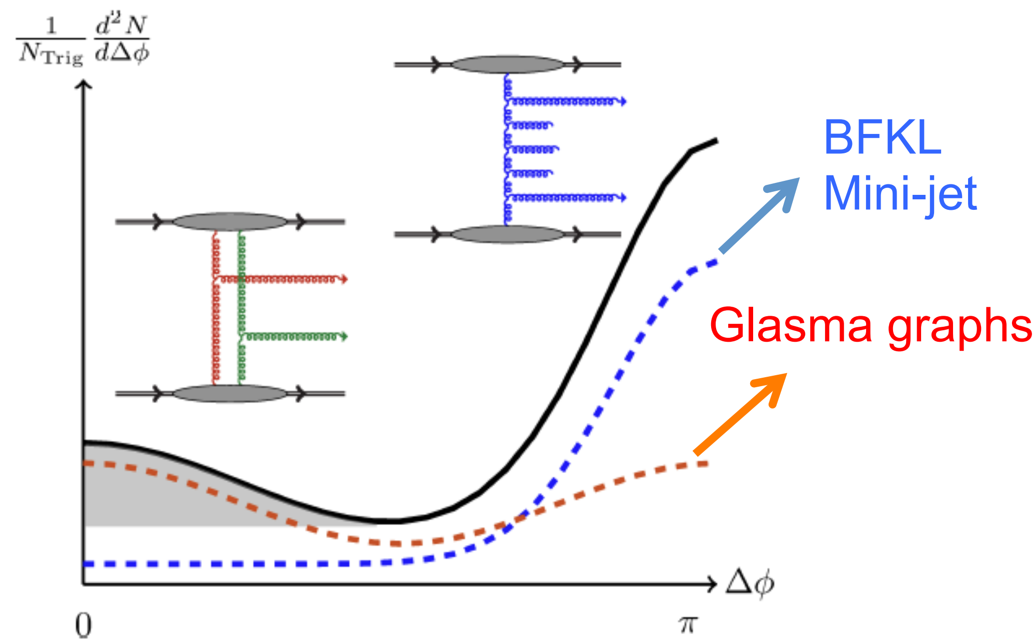
Intrinsic collimated gluon emission
from glasma diagram (CGC)



K. Dusling, R. Venugopalan:
arXiv:1210.3890



Quantum interference of gluons

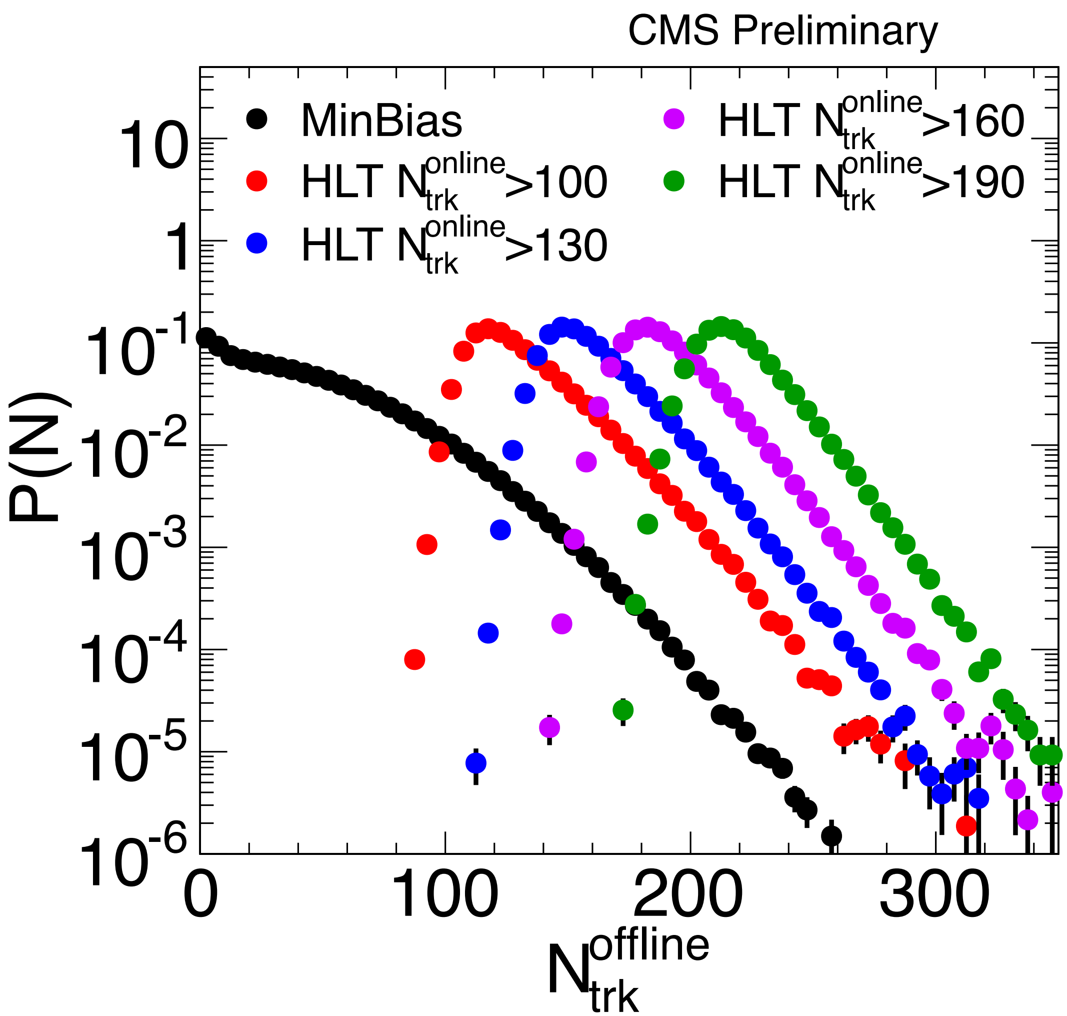


Smoking gun of gluon saturations?

Key difference: initial-state "geometry" driven or not!

2013 pPb run at the LHC

High-multiplicity trigger in pPb at CMS



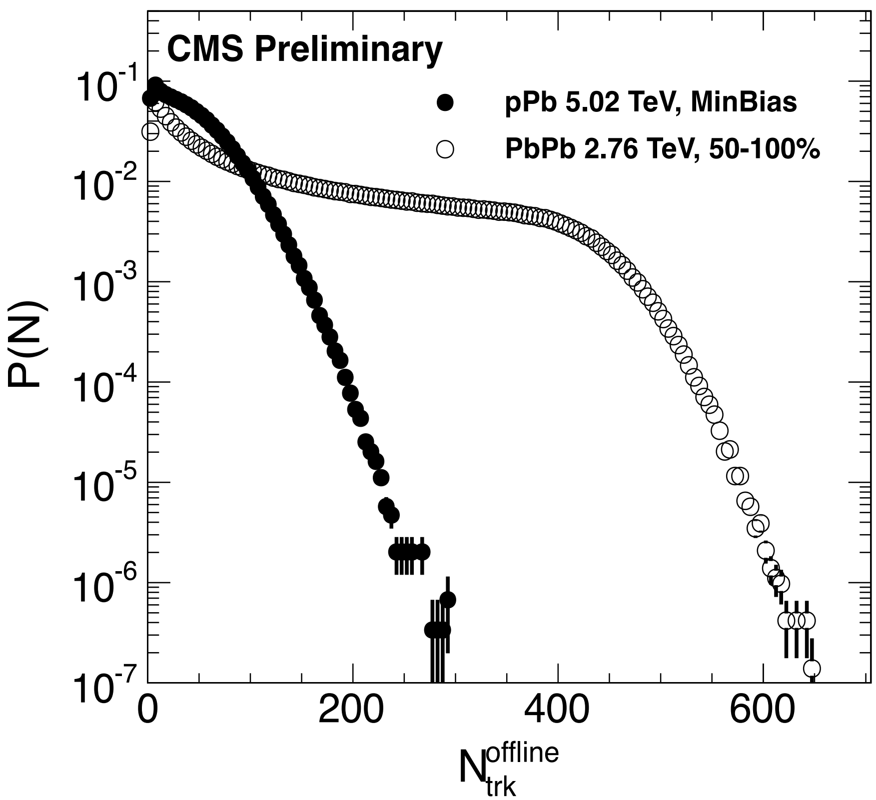
4 different trigger thresholds, each collecting ~20 million events

- Powerful high-level trigger farm: 16K CPU cores
- Online tracking and vertexing

Sampled full 31 nb^{-1} integrated luminosity (60 billion collisions)

Multiplicity distributions in pPb and PbPb

Direct comparison of pPb and PbPb



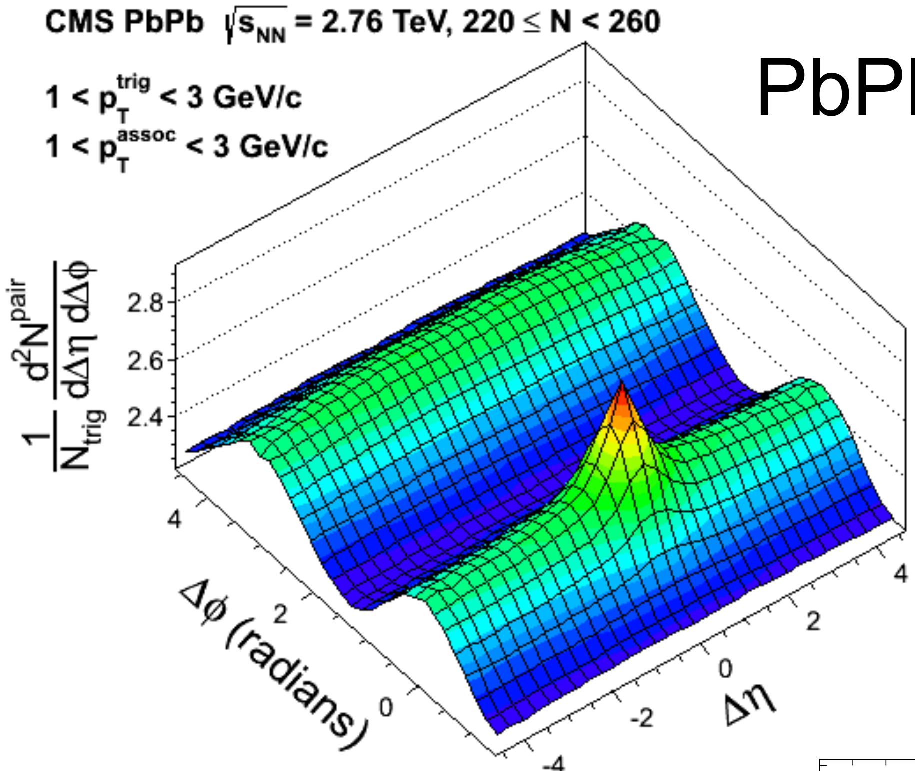
$N_{trk}^{offline}$ bin	PbPb data <Centrality> ± RMS (%)	$\langle N_{trk}^{offline} \rangle$	$\langle N_{trk}^{corrected} \rangle$	pPb data Fraction	$\langle N_{trk}^{offline} \rangle$	$\langle N_{trk}^{corrected} \rangle$
$[0, \infty)$				1.00	40	50±2
[0, 20)	92±4	10	13±1	0.31	10	12±1
[20, 30)	86±4	24	30±1	0.14	25	30±1
[30, 40)	83±4	34	43±2	0.12	35	42±2
[40, 50)	80±4	44	55±2	0.10	45	54±2
[50, 60)	78±3	54	68±3	0.09	54	66±3
[60, 80)	75±3	69	87±4	0.12	69	84±4
[80, 100)	72±3	89	112±5	0.07	89	108±5
[100, 120)	70±3	109	137±6	0.03	109	132±6
[120, 150)	67±3	134	168±7	0.02	132	159±7
[150, 185)	64±3	167	210±9	4×10^{-3}	162	195±9
[185, 220)	62±2	202	253±11	5×10^{-4}	196	236±10
[220, 260)	59±2	239	299±13	6×10^{-5}	232	280±12
[260, 300)	57±2	279	350±15	3×10^{-6}	271	328±14
[300, 350)	55±2	324	405±18	1×10^{-7}	311	374±16

- ➢ Highest multiplicity of ~ 370 explored in pPb
- ➢ Occurs once in every 10 million events (~ 6000 events recorded)
- ➢ Comparable to 55% mid-central PbPb

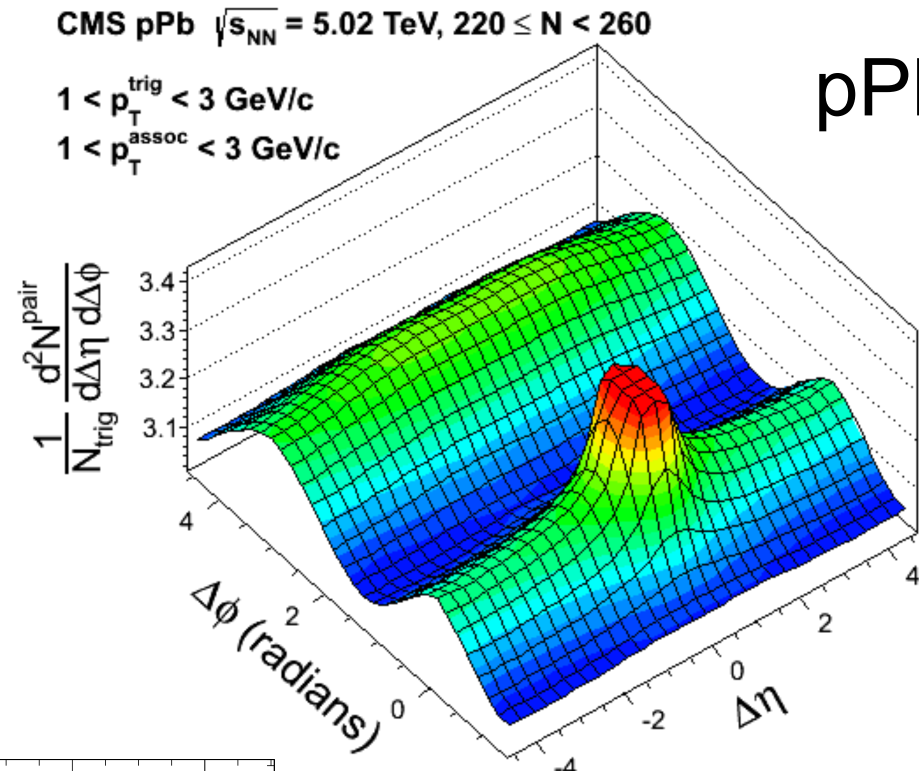
Ridge in PbPb vs pPb

220 ≤ N < 260

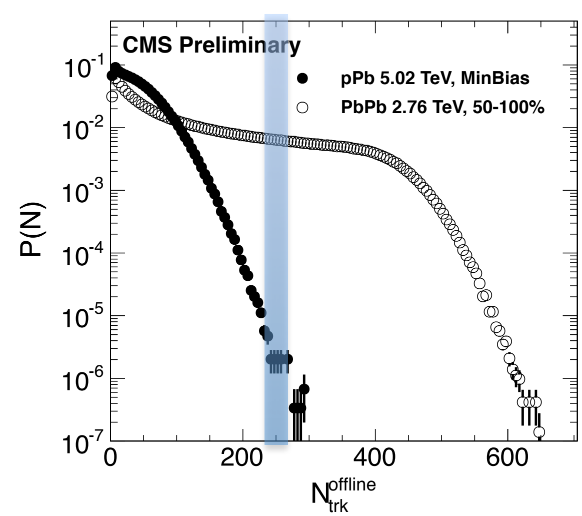
~ 60% centrality



PbPb



pPb



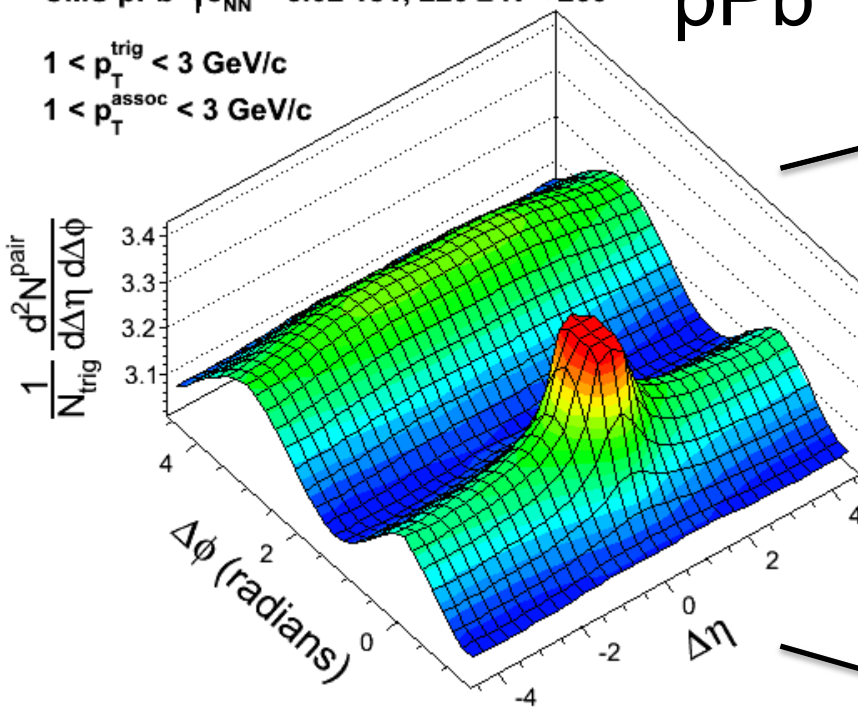
To be submitted to PLB

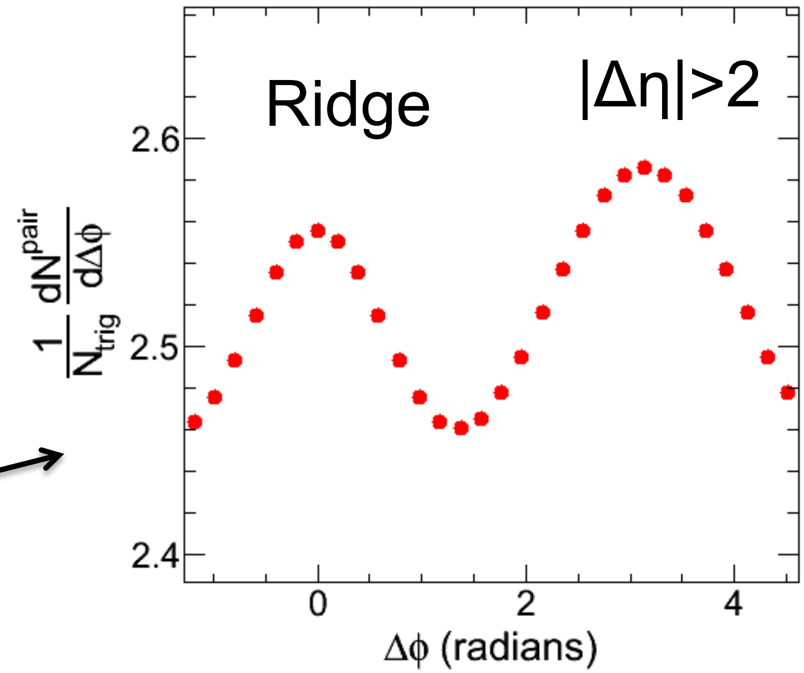
Quantify the ridge correlations

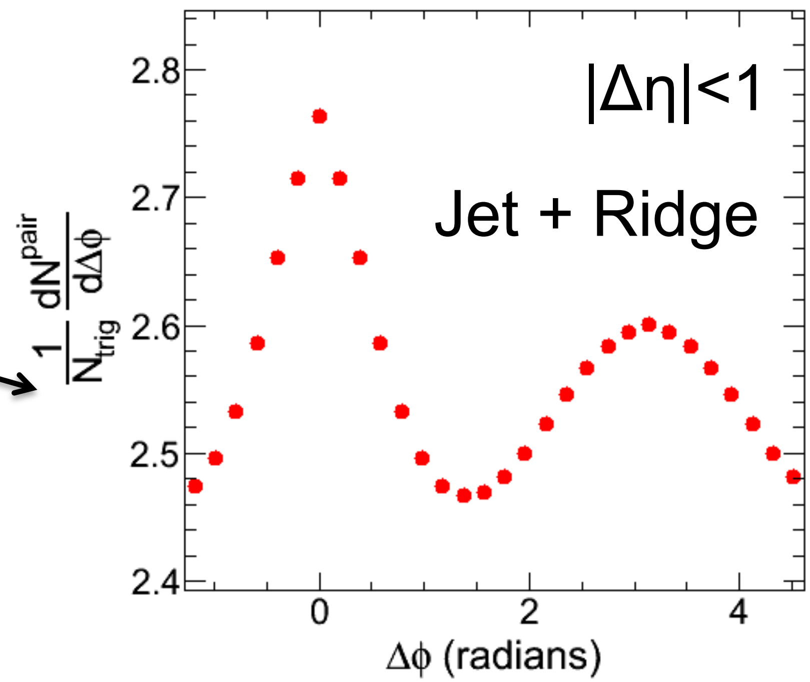
Projection to 1D Δϕ-axis

$220 \leq N < 226$

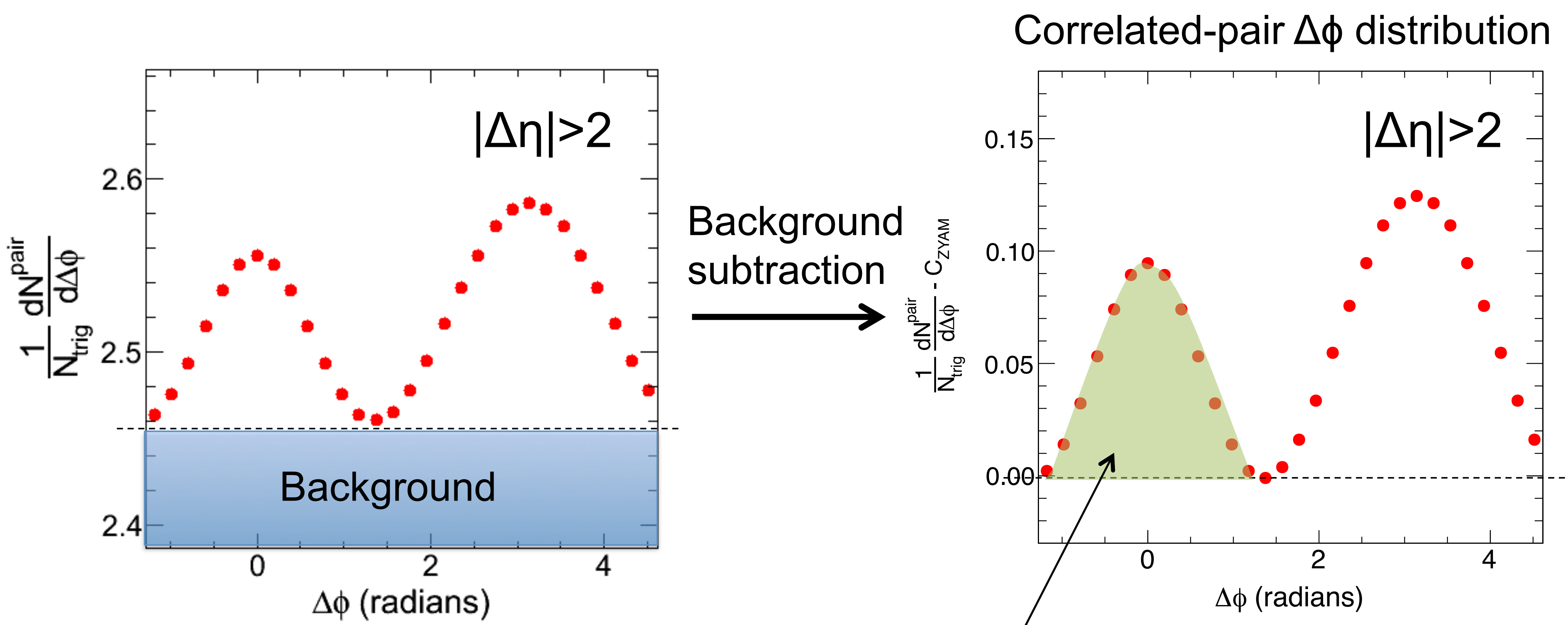
pPb





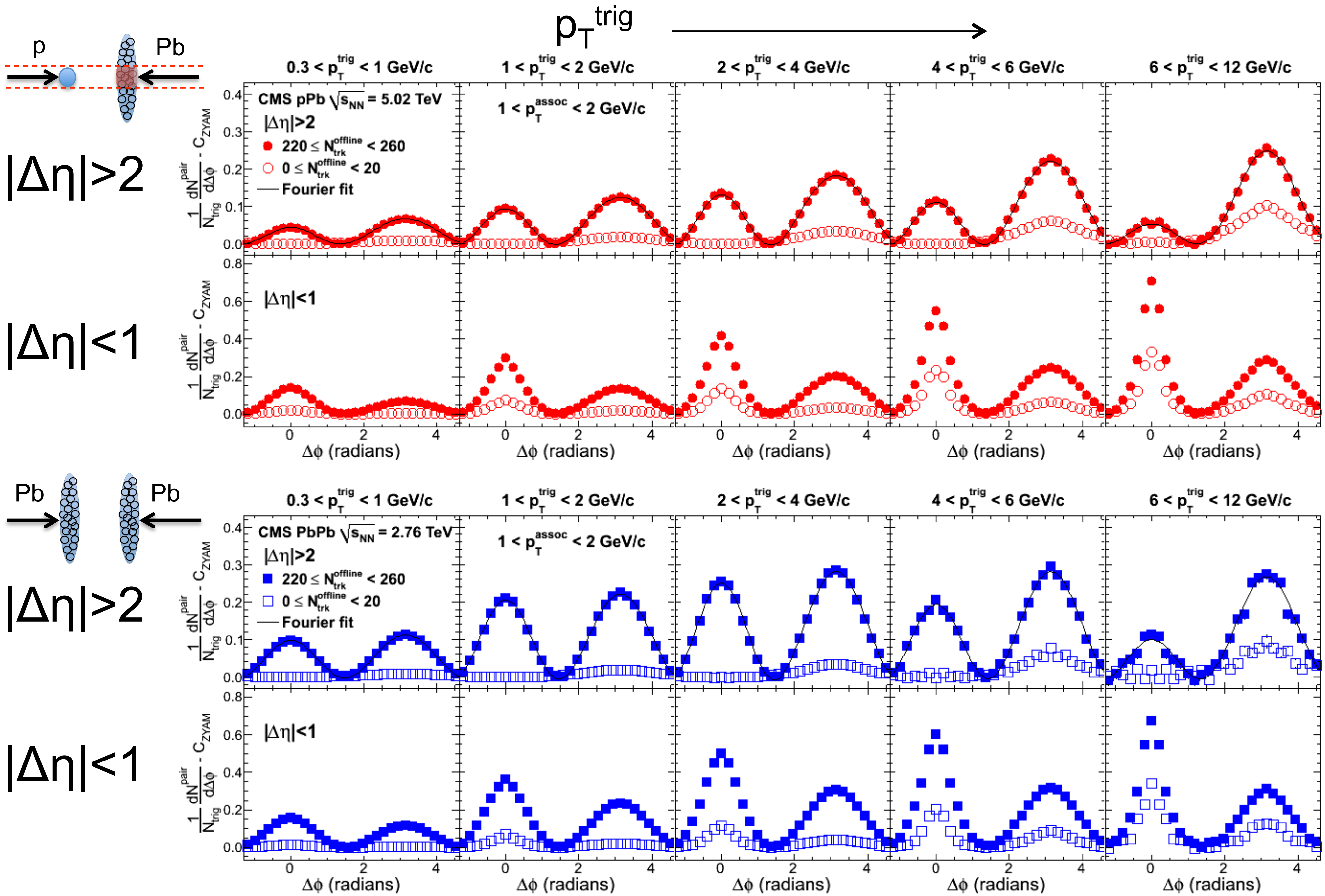


Quantify the ridge correlations



Integrated associated yield:
total number of correlated pairs

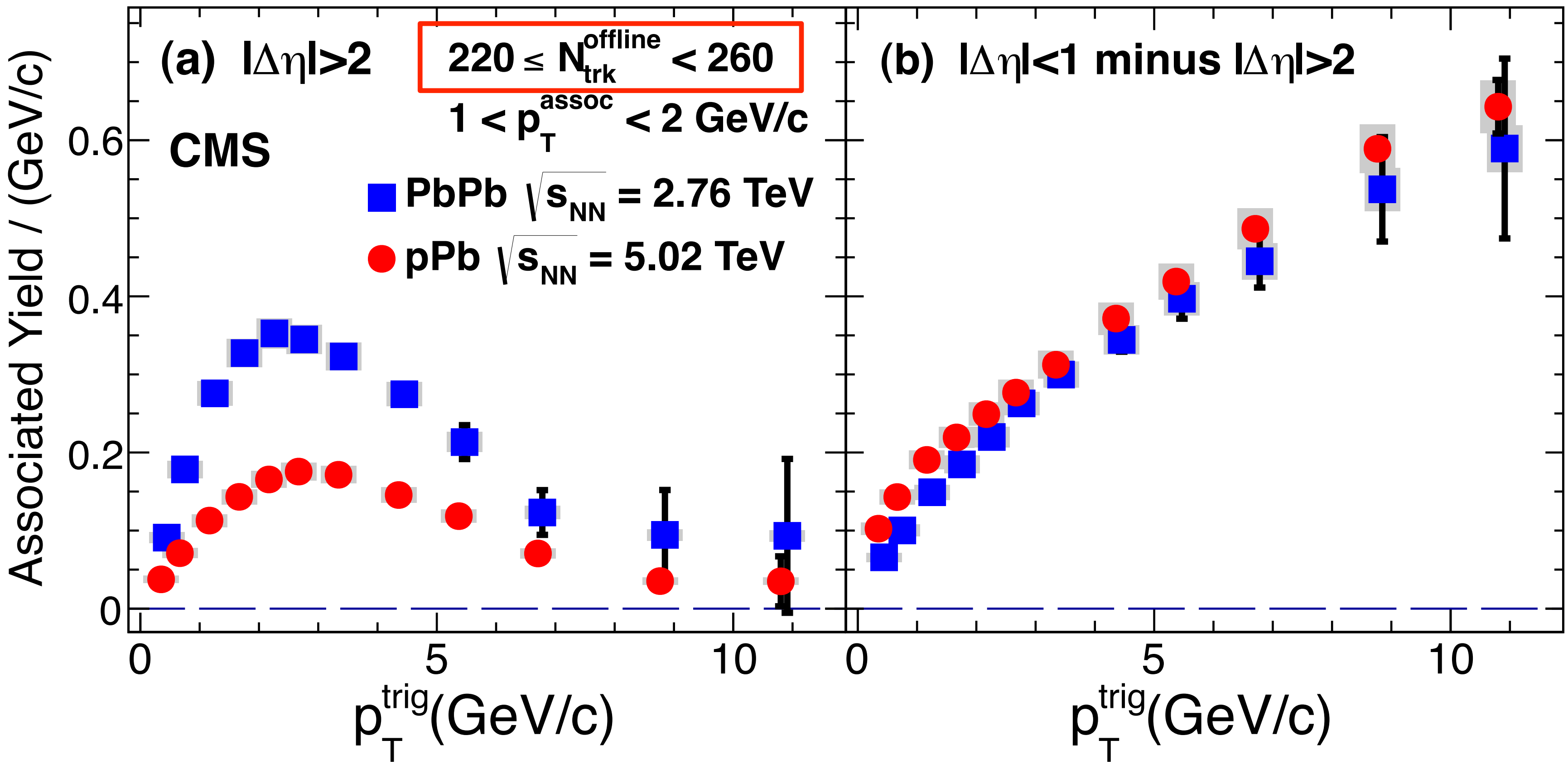
1D Δϕ correlation functions



p_T dependence of associated yield

Ridge region ($|\Delta\eta|>2$)

Jet region ($|\Delta\eta|<1$)



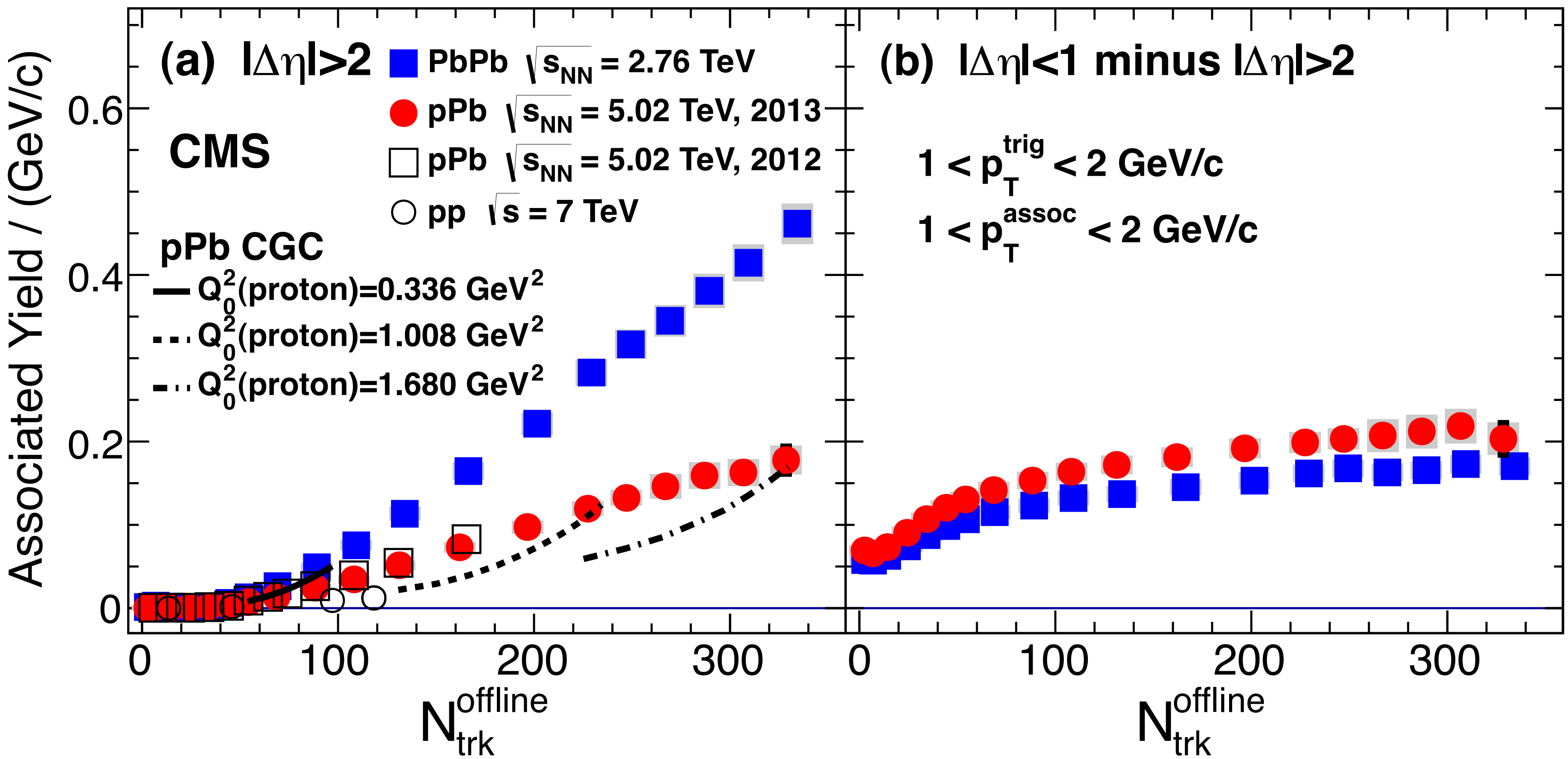
Ridge yield peaks at p_T^{trig} ~ 2-3 GeV/c

Jet yield monotonically increase with p_T^{trig}

Similar trend for pPb and PbPb

Multiplicity dependence of associated yield

Ridge region (|Δη|>2) Jet region (|Δη|<1)



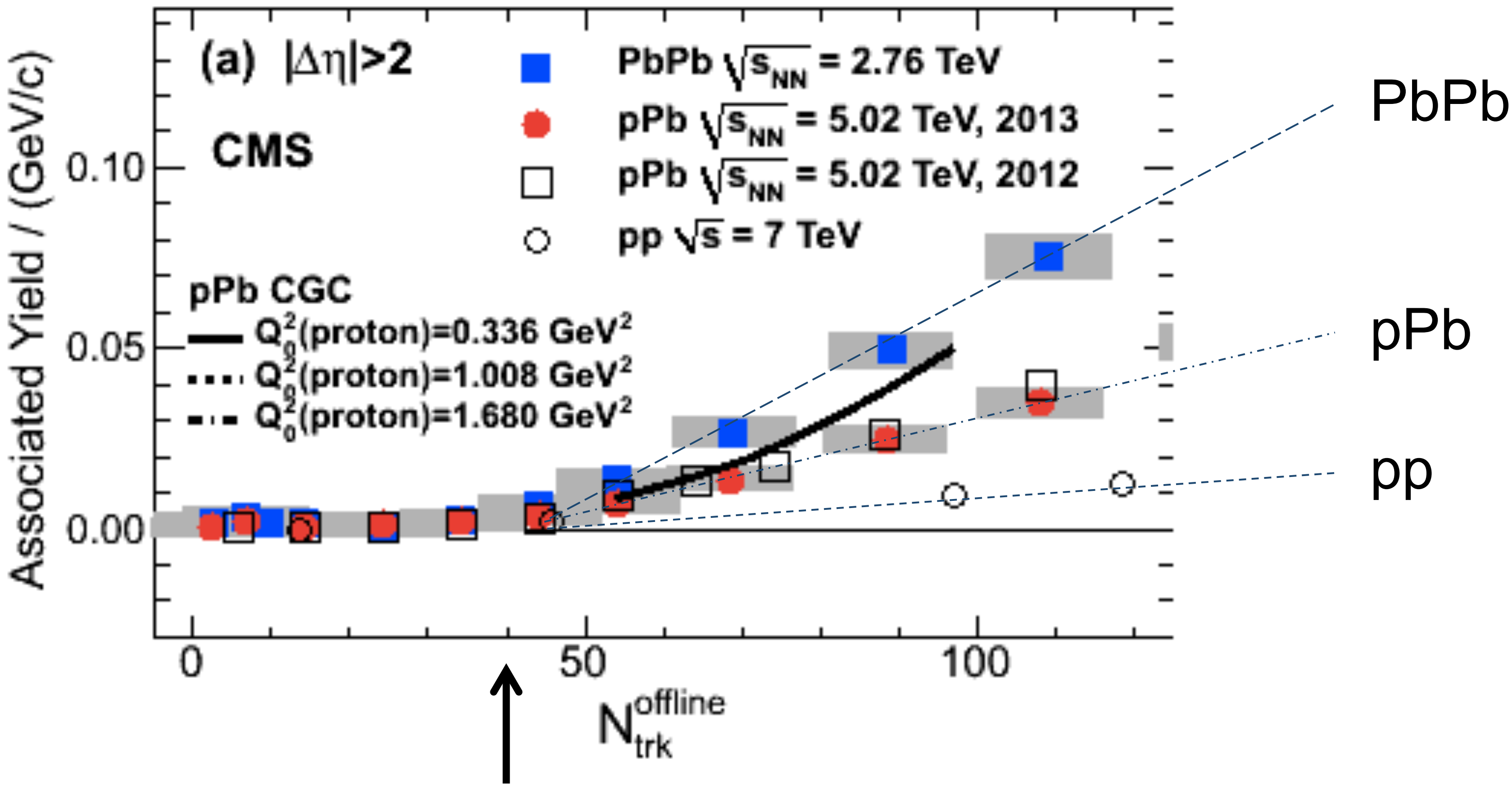
- Linear rise with N
- PbPb > pPb > pp

Weak dependence of N

Similar trend for pp, pPb and PbPb

Multiplicity dependence of associated yield

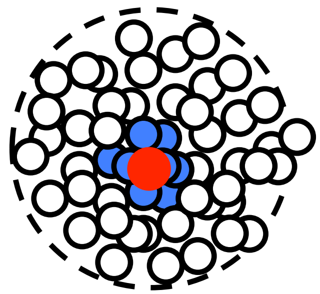
Zoom into low multiplicity region



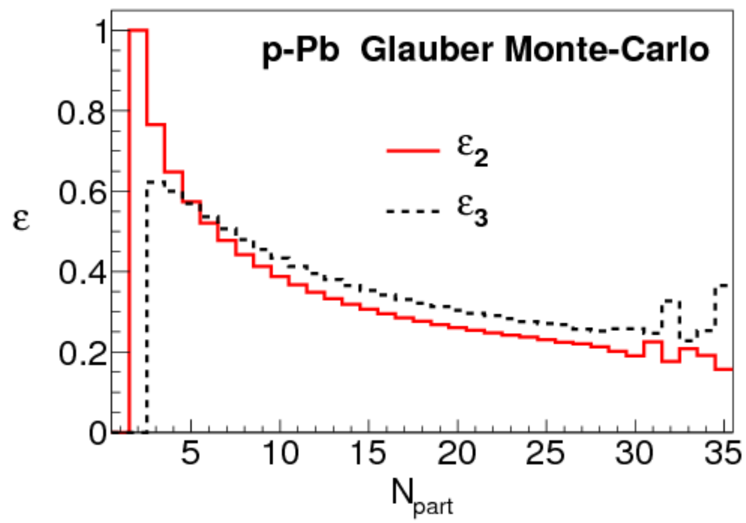
Universal turn-on of the ridge at N ~ 40?

Hydrodynamics at its edge: pp and pA?

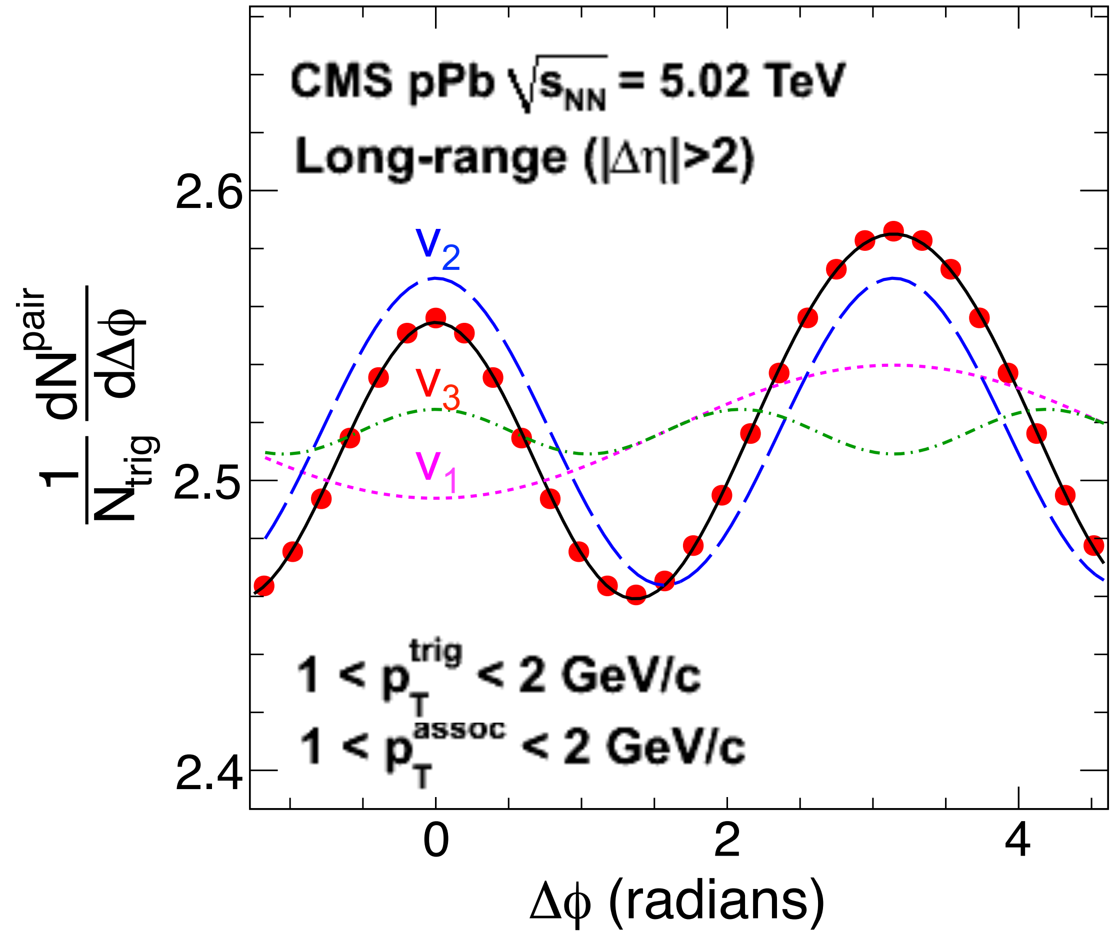
If accepting the concept of geometry fluctuation, hydrodynamic flow in pA could be possible



Initial-state eccentricity



P. Bozek, Phys.Rev. C85 (2012) 014911

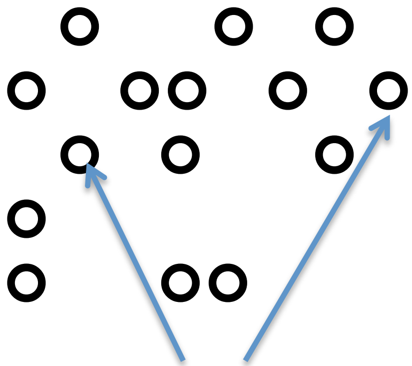


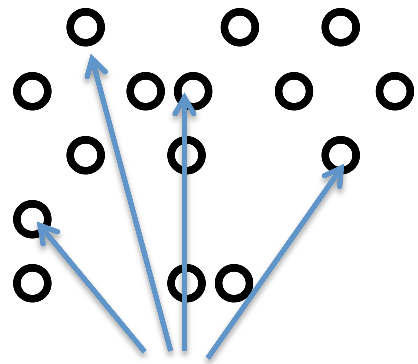
Perfectly described by just v_1, v_2 and v_3!

Issues: smaller system, shorter lifetime, larger viscous correction, initial condition uncertain. Is hydro still valid? Where is the limit?

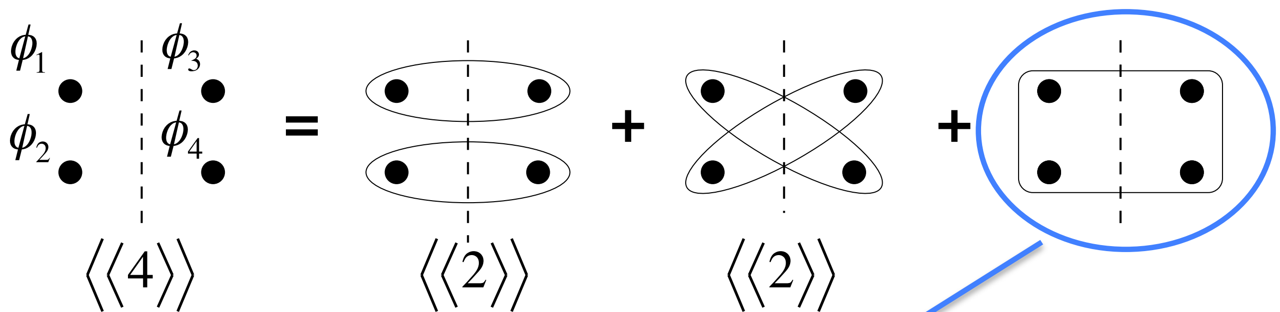
Flow from multi-particle correlations

- Is the Ridge just a two-particle effect or involves more particles
- Flow is a multi-particle phenomenon, can be probed via cumulant





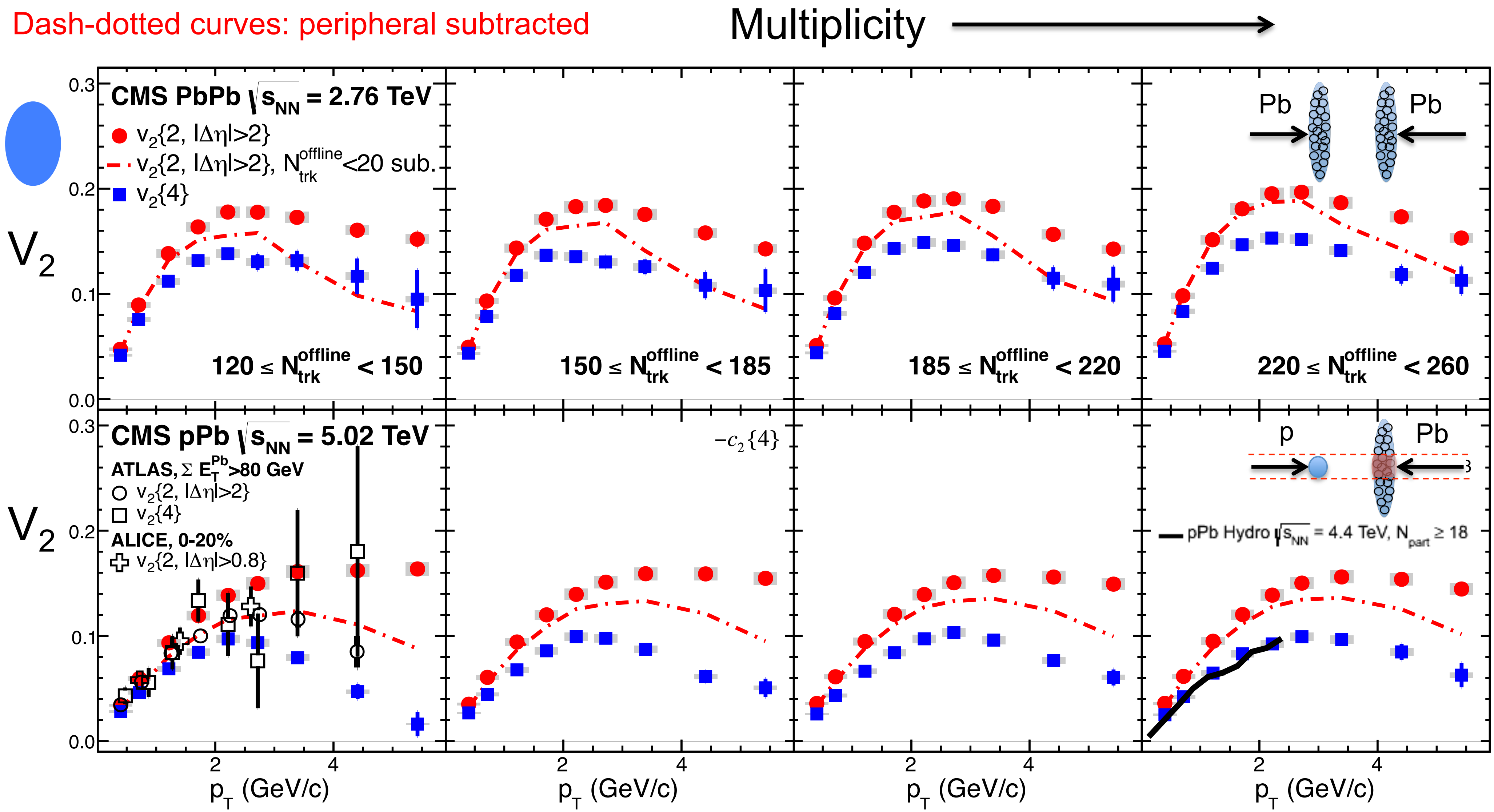
$$\langle\langle 2\rangle\rangle = \langle \cos 2(\phi_1 - \phi_2)\rangle \ (\mathrm{v}_2\{2\}) \qquad \langle\langle 4\rangle\rangle = \langle \cos 2(\phi_1 + \phi_2 - \phi_3 - \phi_4)\rangle$$



4th-order cumulant: $$c_n\{4\} = \langle\langle 4\rangle\rangle - 2\cdot\langle\langle 2\rangle\rangle^2$$

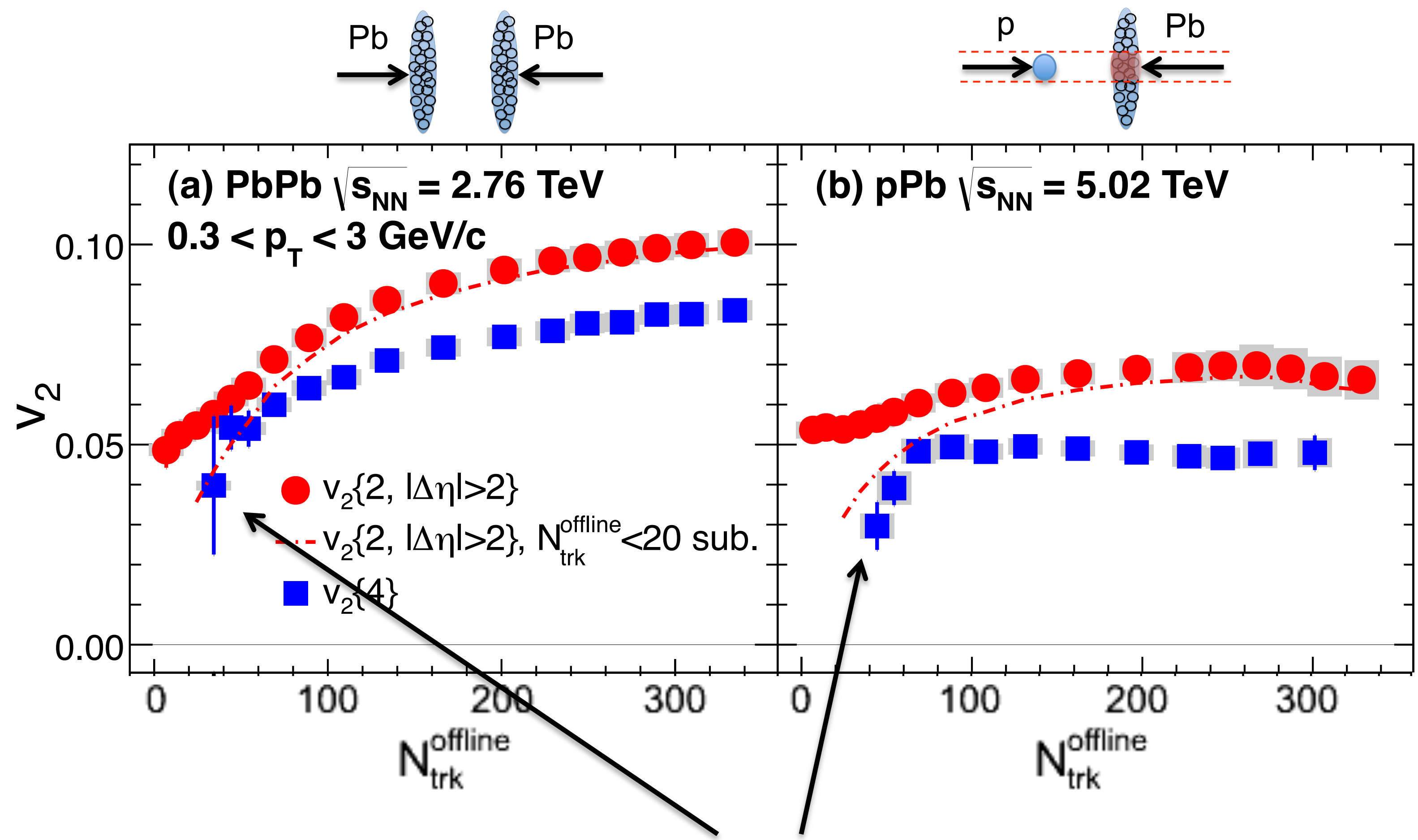
$$\boxed{\mathrm{v}_2\{4\} = \sqrt[4]{-c_2\{4\}}}$$

p_T dependence of elliptic flow (v_2)



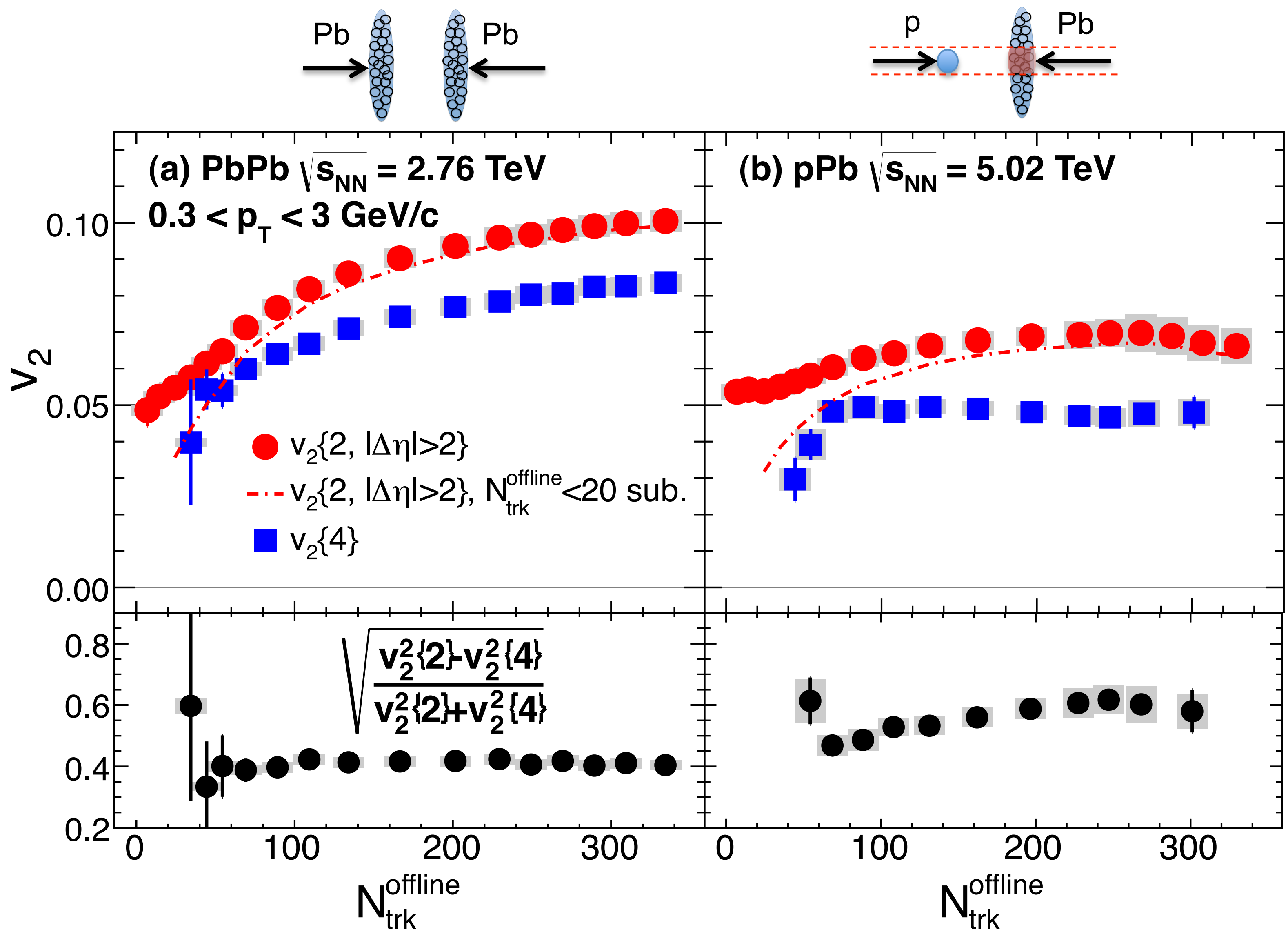
- $v_2\{2\} > v_2\{4\}$ as expected due to flow fluctuations and nonflow
- Similar p_T dependence of v_2: rise and fall, but smaller in pPb

Multiplicity dependence of elliptic flow (v_2)



$v_2\{4\}$ turns on at N ~ 40: onset of collective phenomena?

Multiplicity dependence of elliptic flow (v_2)



Extract "v_2 fluctuations"

$$v_2\{2\} = \sqrt{< v_2 >^2 + \sigma_{v_2}^2}$$

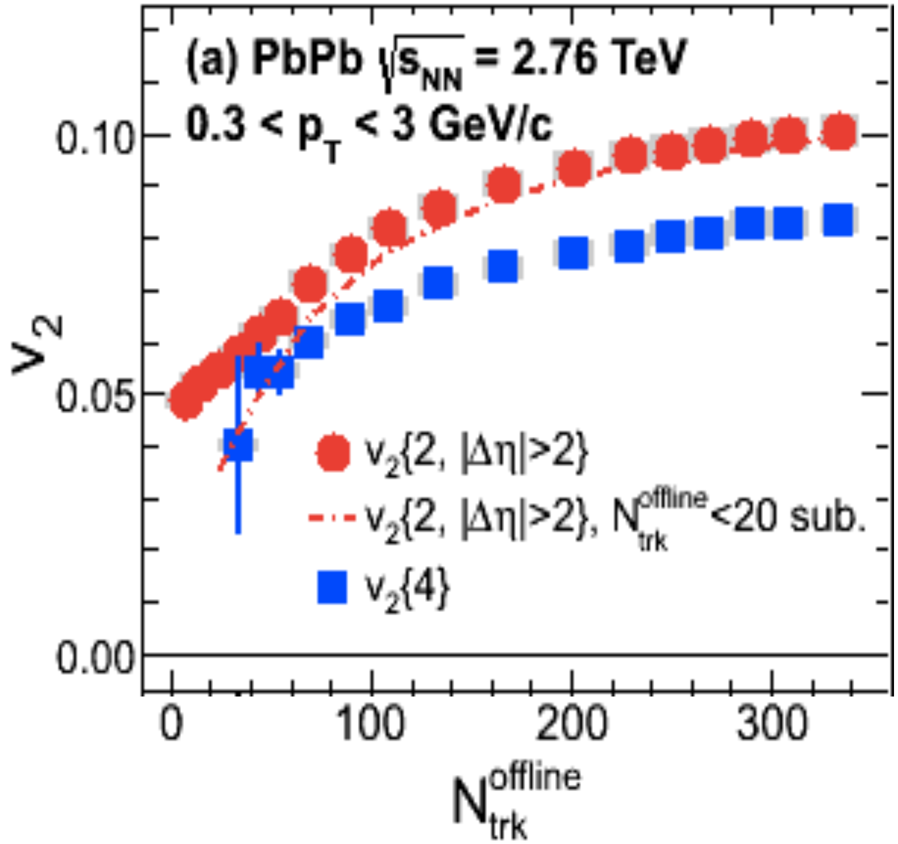
$$v_2\{4\} = \sqrt{< v_2 >^2 - \sigma_{v_2}^2},$$

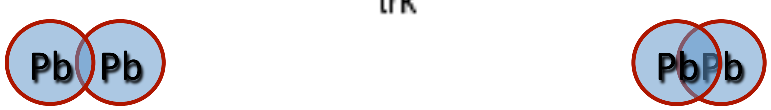
$$\frac{\sigma_{v_2}}{v_2} = \sqrt{\frac{v_2^2\{2\} - v_2^2\{4\}}{v_2^2\{2\} + v_2^2\{4\}}}.$$

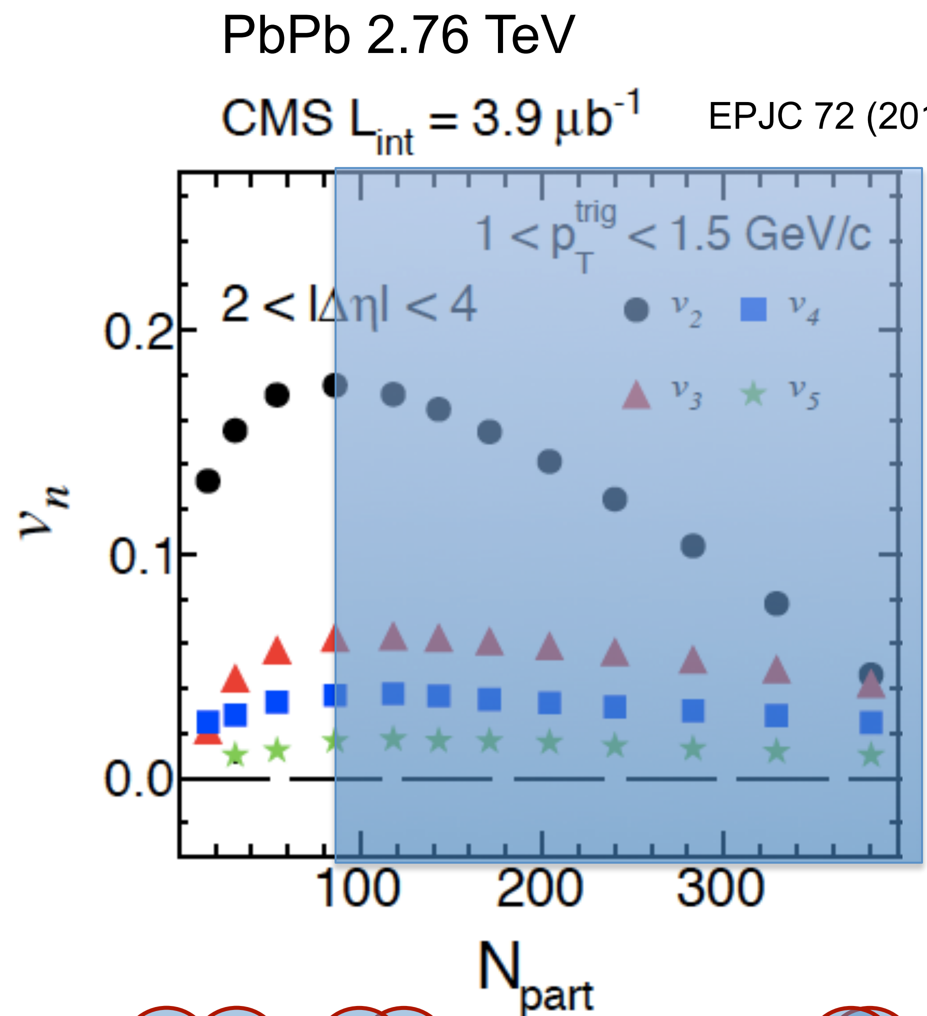
Larger in pPb with moderate multiplicity dependence

Multiplicity dependence of elliptic flow (v_2)

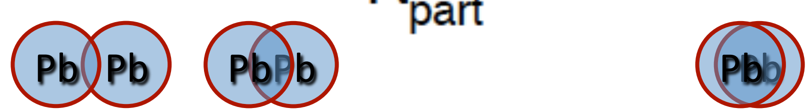
v_2 in PbPb increases
as eccentricity decreases?







EPJC 72 (2012) 2012

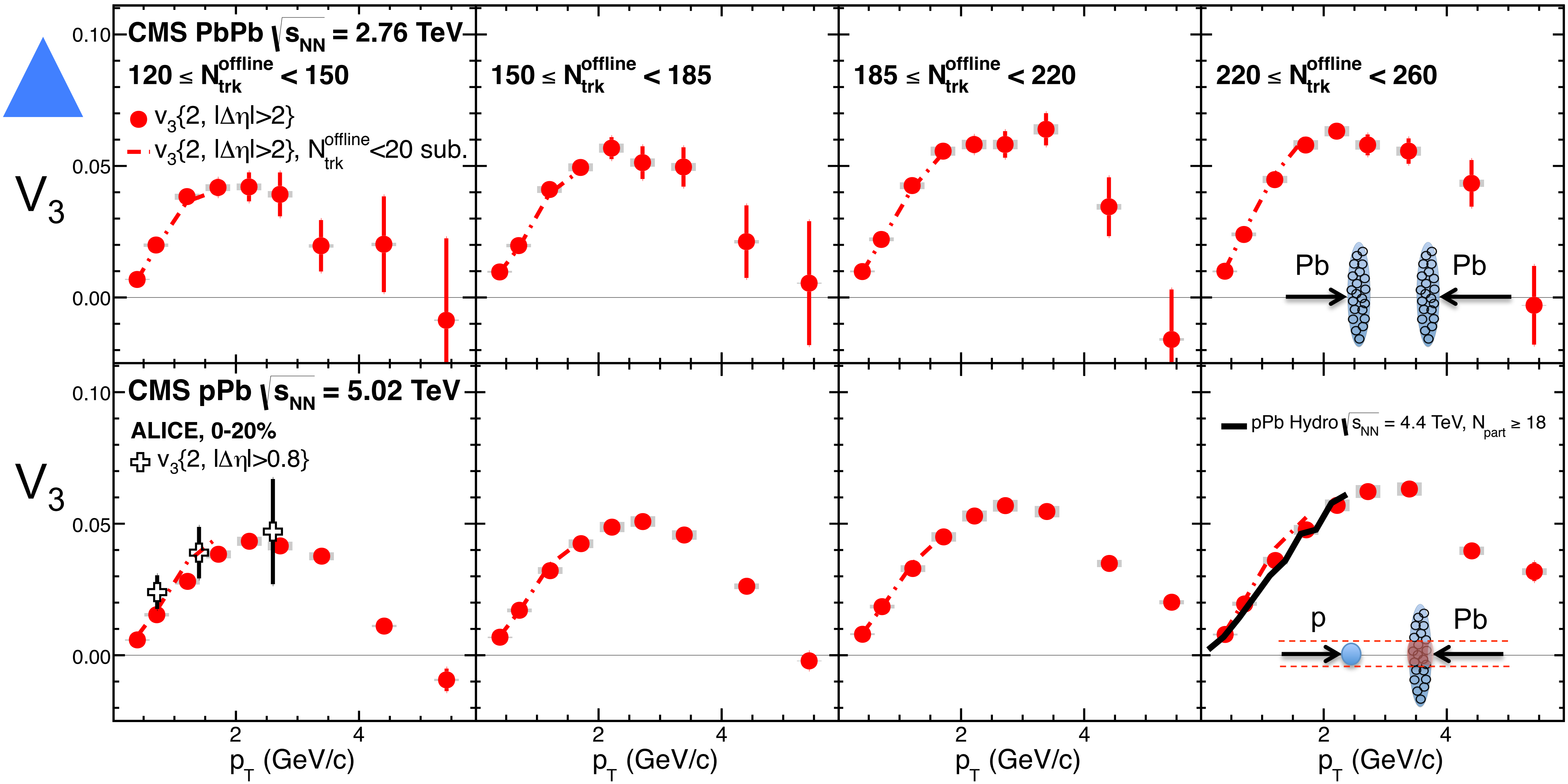


- Ideal hydro. breaks down for very peripheral PbPb;
- Finite system size leads to larger viscous correction

p_T dependence of triangular flow (v_3)

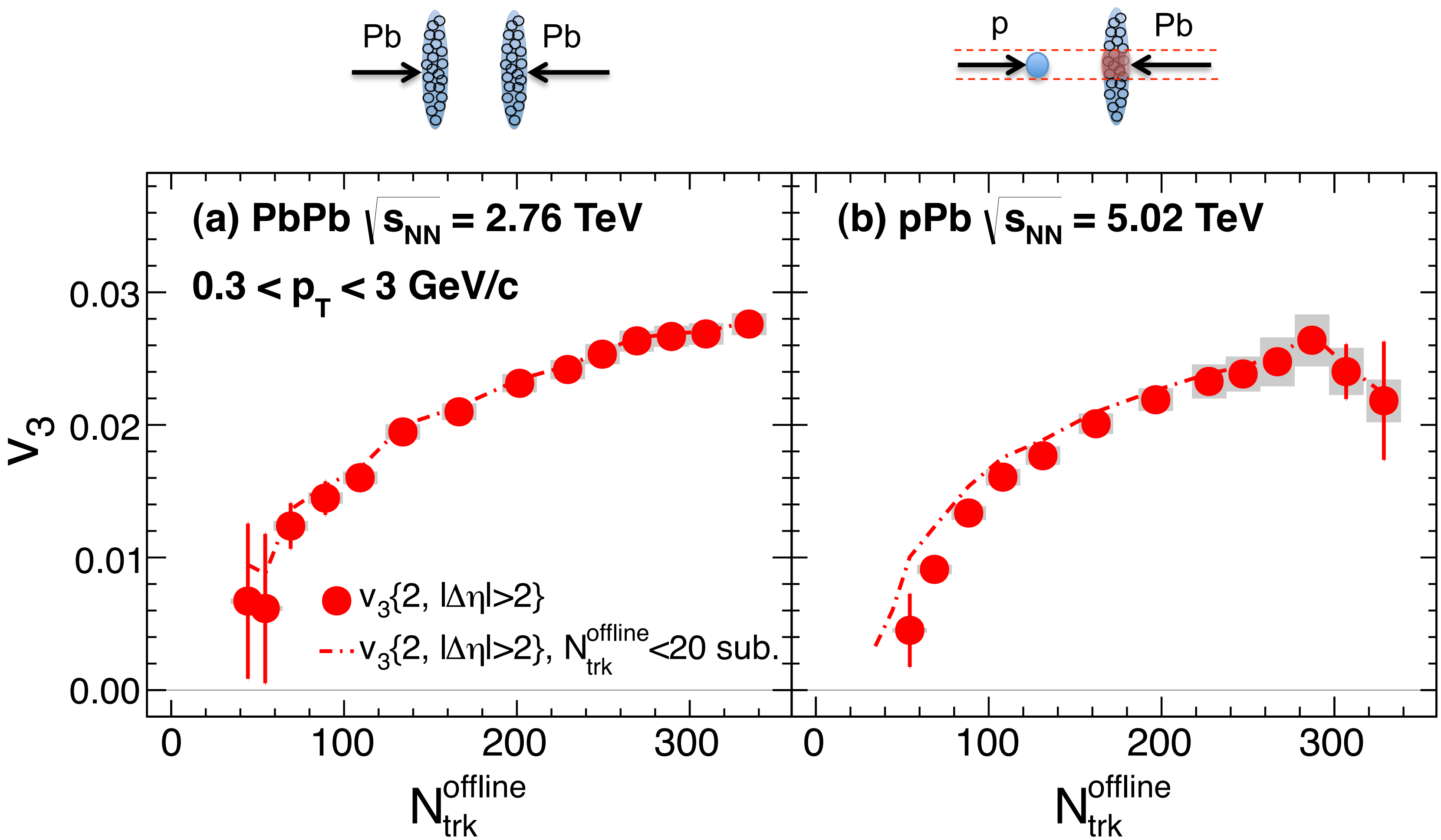
Dash-dotted curves: peripheral subtracted

Multiplicity →



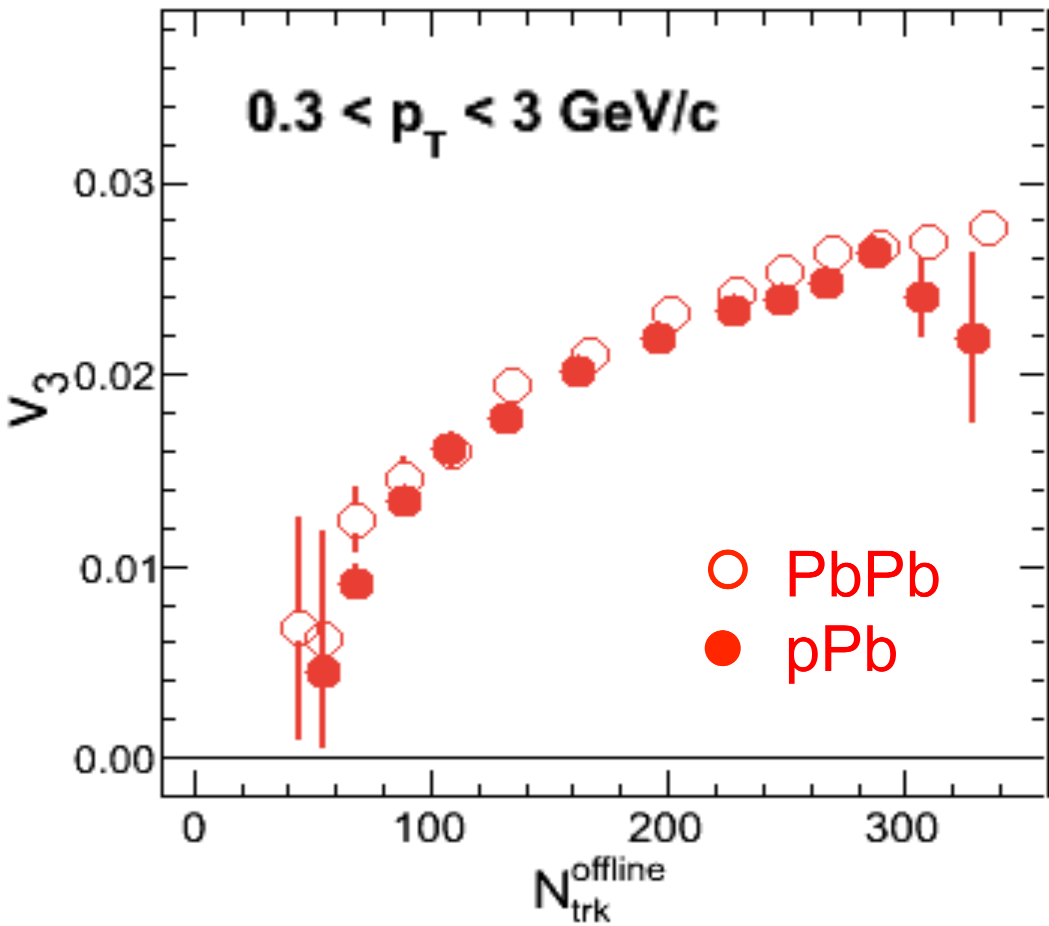
Striking similarity of v_3 for PbPb and pPb systems with drastically different collision geometry and its fluctuations

Multiplicity dependence of triangular flow (v_3)



Striking similarity of v_3 for PbPb and pPb systems with drastically different collision geometry and its fluctuations

Multiplicity dependence of triangular flow (v_3)

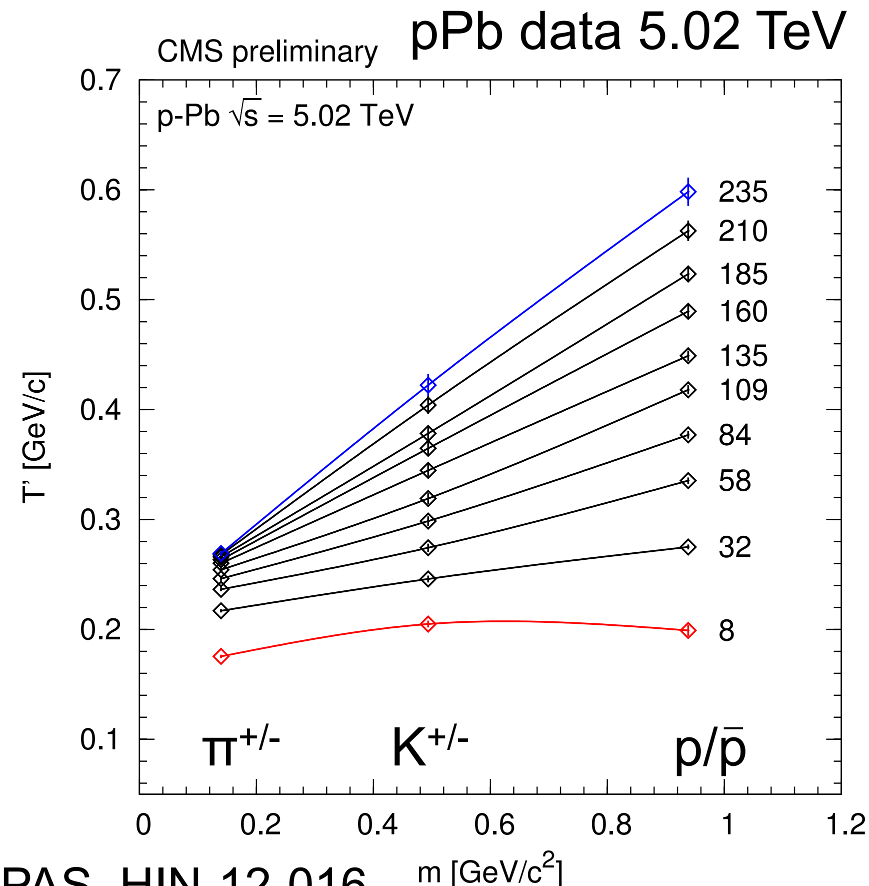


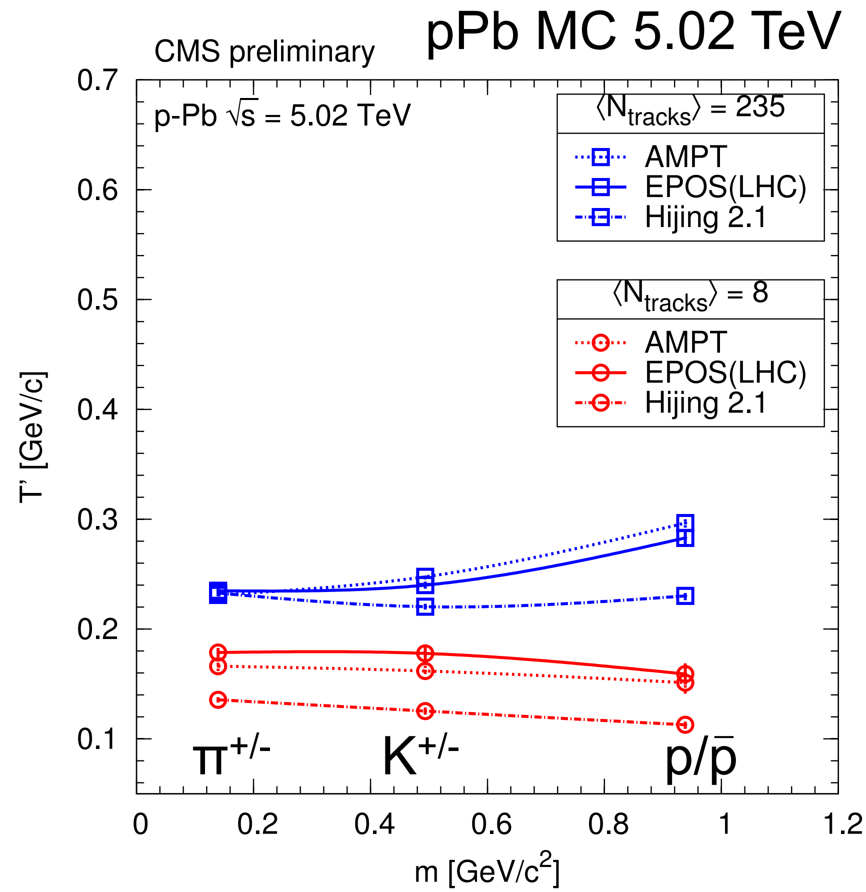
Striking similarity of v_3 for PbPb and pPb systems with drastically different collision geometry and its fluctuations

Can this be understood in hydrodynamics?

Any other evidence of hydrodynamic flow?

Inverse slope, T_{slope}, of m_T distributions: $\frac{1}{m_T}\frac{dN}{dm_T} \sim \exp(-\frac{m_T}{T_{slope}})$





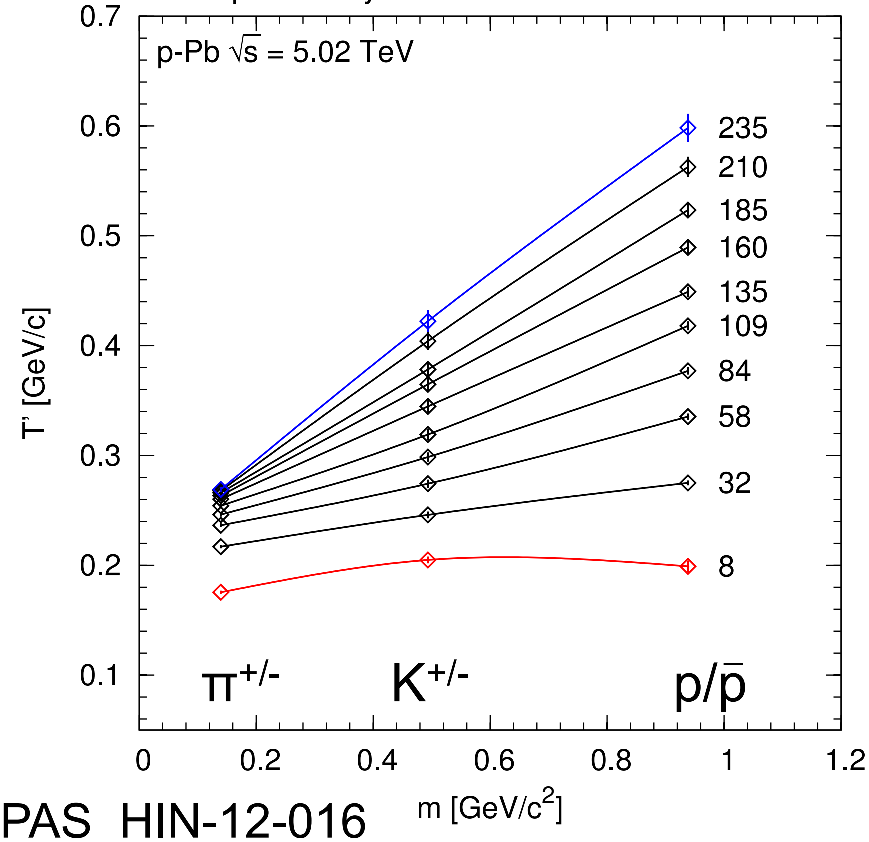
CMS PAS HIN-12-016

- T_{slope} linear with particle mass; proportionality increasing with N
- No such trend observed in MC models (AMPT, HIJING)

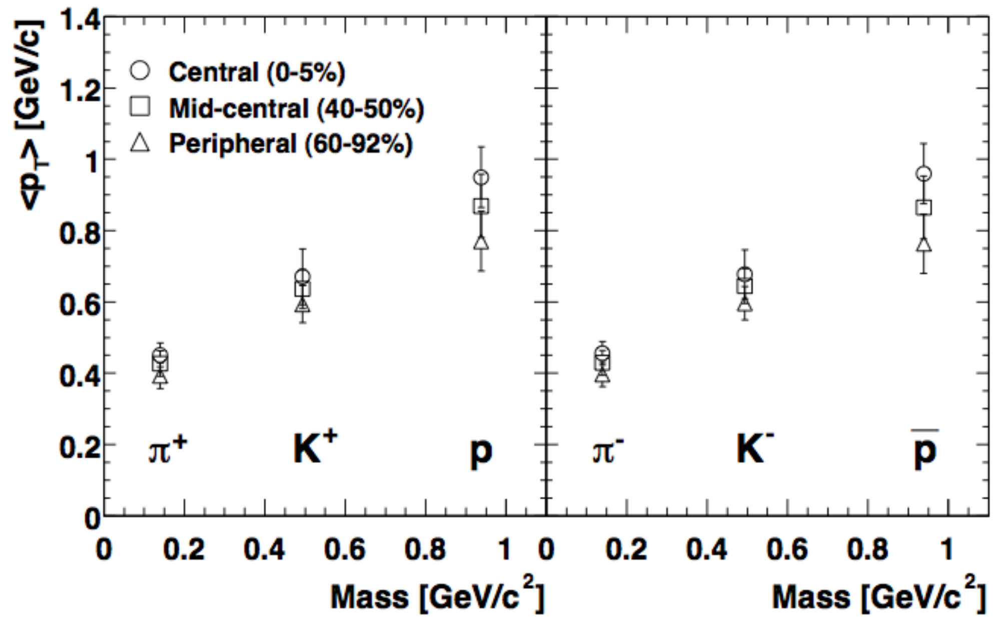
Any other evidence of hydrodynamic flow?

Inverse slope, T_{slope}, of m_T distributions: $\frac{1}{m_T}\frac{dN}{dm_T} \sim \exp(-\frac{m_T}{T_{slope}})$

pPb data 5.02 TeV



AuAu 200 GeV



CMS PAS HIN-12-016

- Similar trend as observed in AA collisions
- Radial flow effect: $T_{slope} = T_{freeze\text{-}out} + m\langle u\rangle^2$?

radial flow velocity

Summary

Observation of the "Ridge" in high-multiplicity pp and pPb at the LHC opened up exciting new opportunities for studying QCD in high-density environment.

New results from 2013 pPb run, and a direct comparison to PbPb *(who is helping whom?)*

- Similar multiplicity and p_T dependence of associated yield, elliptic (v_2) and triangular (v_3) flow in PbPb and pPb
- Associated yield turns on at N ~ 40, bigger in PbPb than pPb
- Large v_2 from 4-particle correlations in pPb, turning on at N ~ 40
- Significant v_3 in pPb, strikingly similar to PbPb

Many theoretical efforts are ongoing:

- Is it collective flow, or final-state interactions? In many aspects consistent
- However, a big challenge to understand hydro in pp and pA: *P. Bozek (arXiv:1304.3044), B. Schenke (arXiv:1304.3403)* etc.
- If it is flow, is there jet-medium interaction?
- What role does CGC play in this very-high-density gluon state?

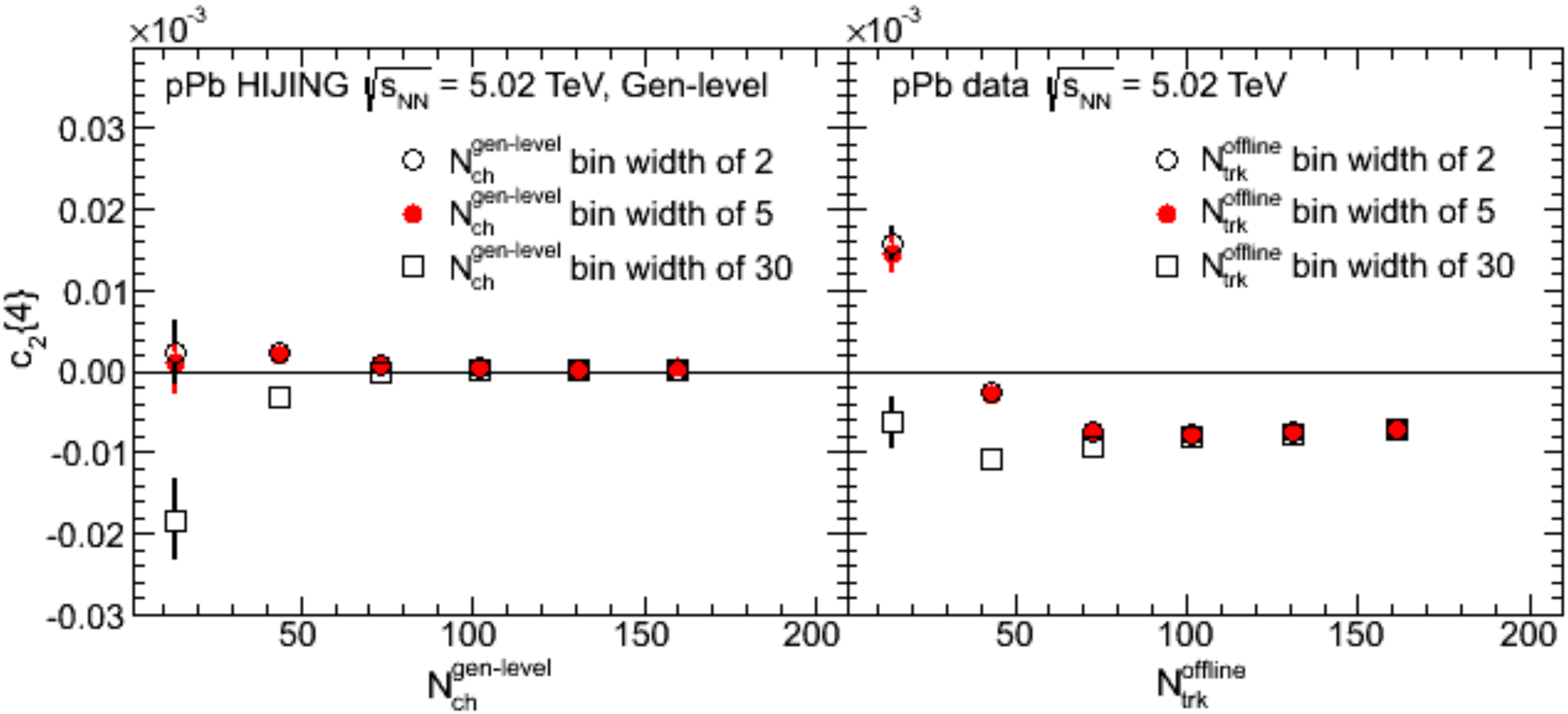
Summary

"pA is like a litmus test. Until we understand pA from our understanding of pp and AA, we cannot claim to have a deep understanding of pp and AA."

Wit Busza

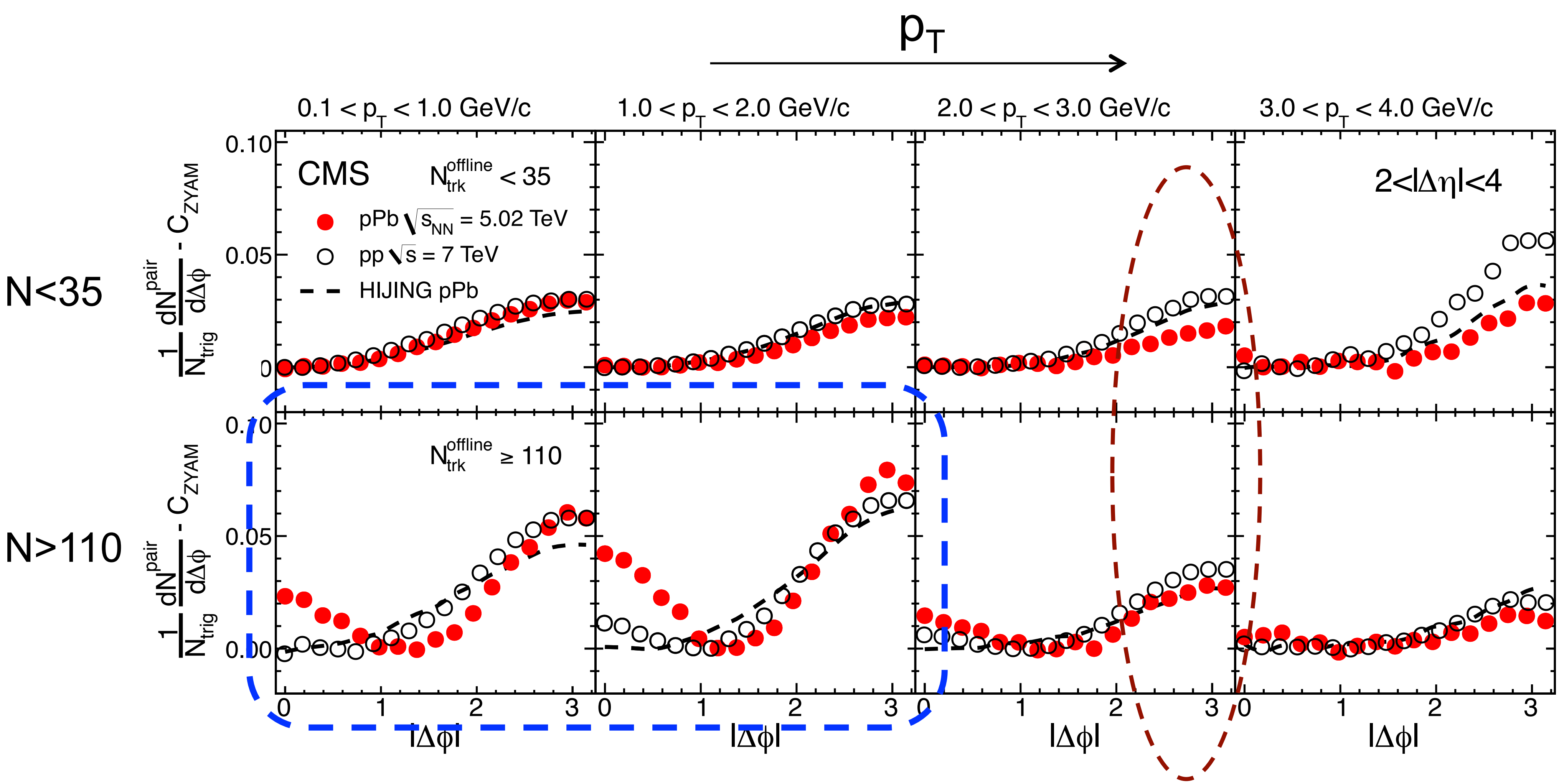
Stay tuned!

Backups



×10⁻³
pPb HIJING $\sqrt{s_{NN}}$ = 5.02 TeV, Gen-level
$N_{ch}^{gen-level}$ bin width of 2
$N_{ch}^{gen-level}$ bin width of 5
$N_{ch}^{gen-level}$ bin width of 30
pPb data $\sqrt{s_{NN}}$ = 5.02 TeV
$N_{trk}^{offline}$ bin width of 2
$N_{trk}^{offline}$ bin width of 5
$N_{trk}^{offline}$ bin width of 30
$c_2\{4\}$
0.03
0.02
0.01
0.00
-0.01
-0.02
-0.03
50
100
150
200
$N_{ch}^{gen-level}$
$N_{trk}^{offline}$

Quantify the ridge correlations



Ridge most prominently at:

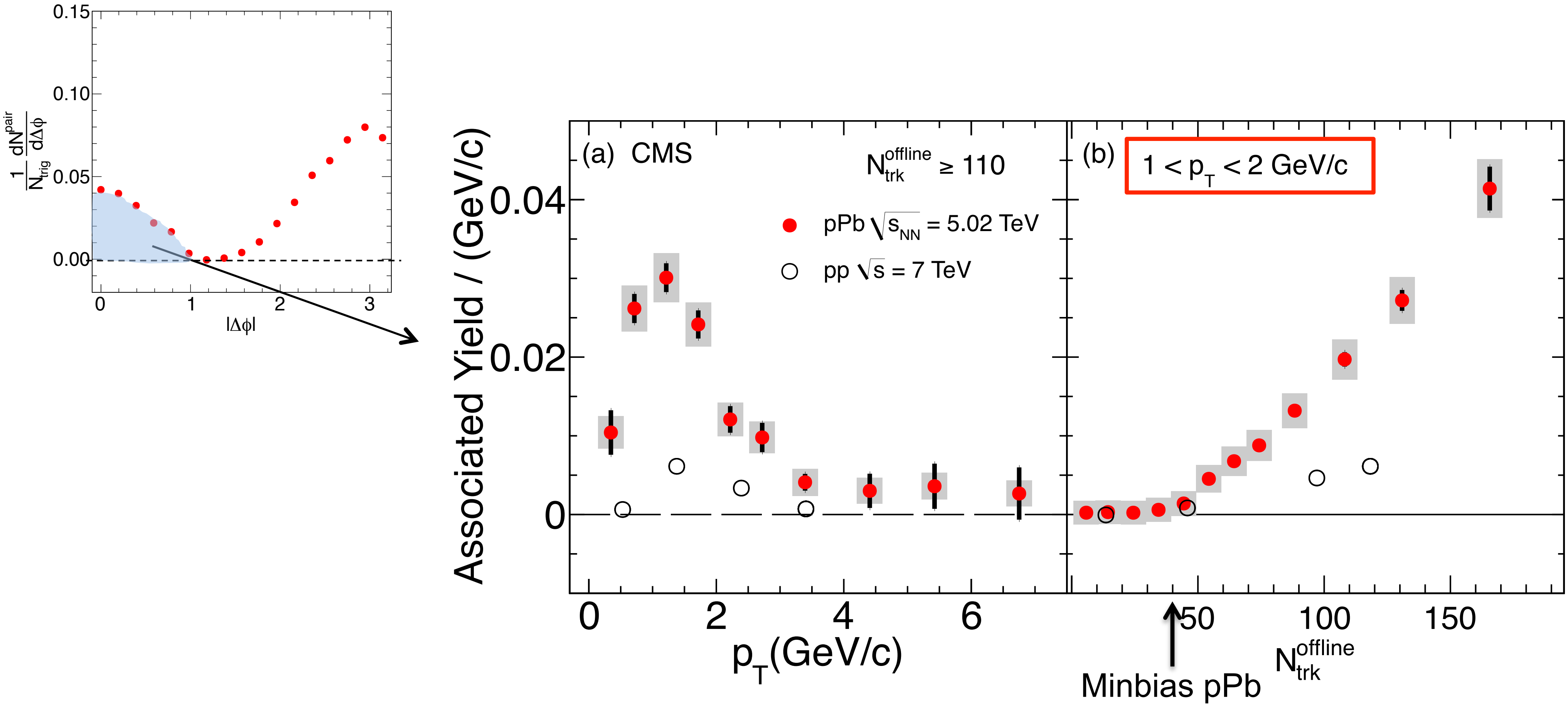
- high multiplicity, N > 110
- intermediate p_T ~ 1 GeV/c

Away-side suppression in pPb?

Stronger ridge in pPb than in pp at fixed N!

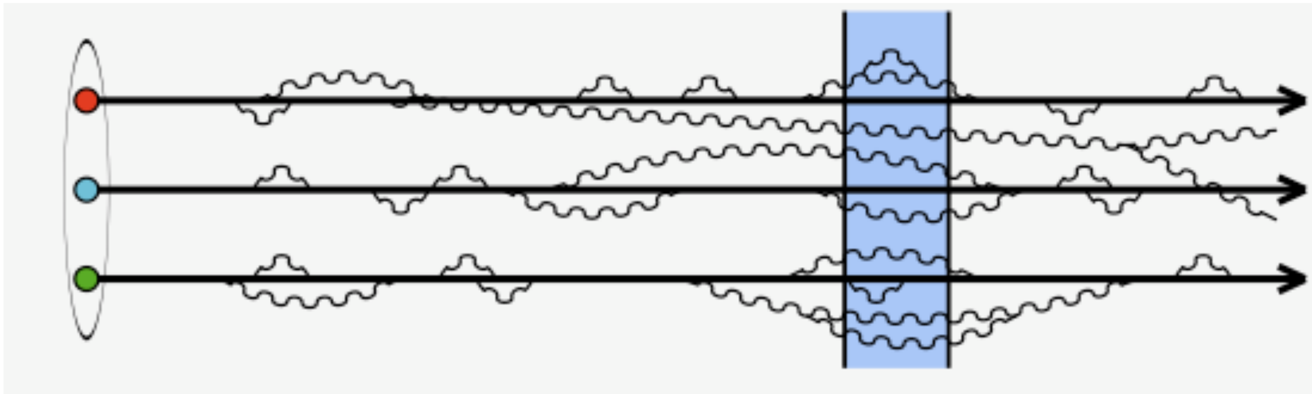
Quantify the ridge correlations

Quantify the ridge

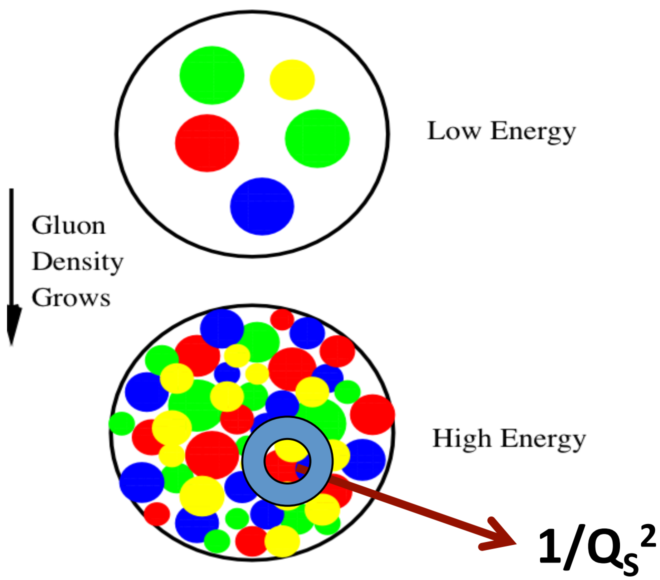


- Magnitude of the ridge is much large in pPb than in pp
- "Rise and Fall" as a function of p_T, similar to pp (even PbPb)!
- Become significant at N=40-50 and linearly increases, similar to pp!

Ridge arising from gluon saturation



At short time scale, many gluons excited in fast moving proton

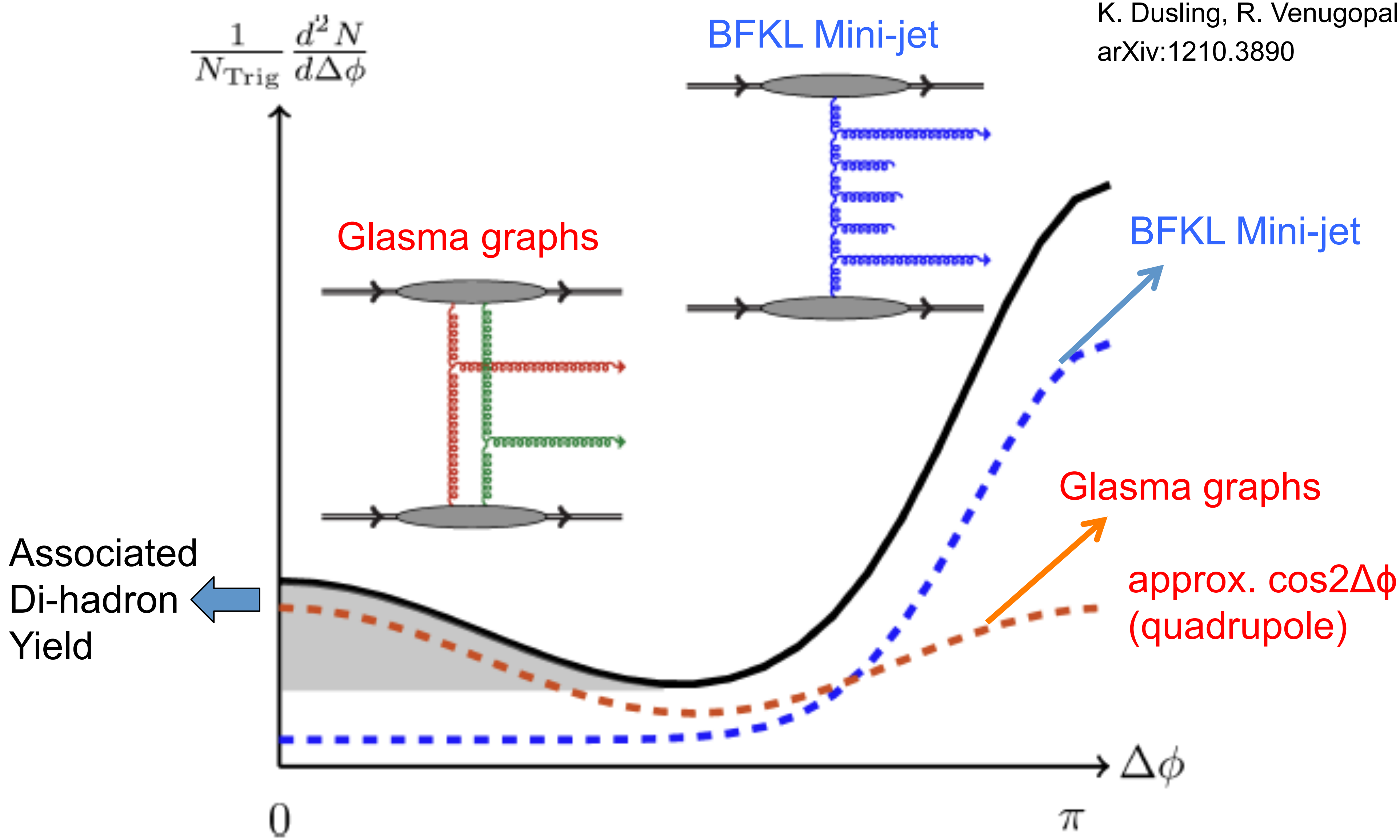


The gluon density saturates at
a maximal value of $1/\alpha_S$ ➔ gluon saturation

$Q_s(x)$: semihard scale

Ridge arising from gluon saturation

K. Dusling, R. Venugopalan: arXiv:1210.3890

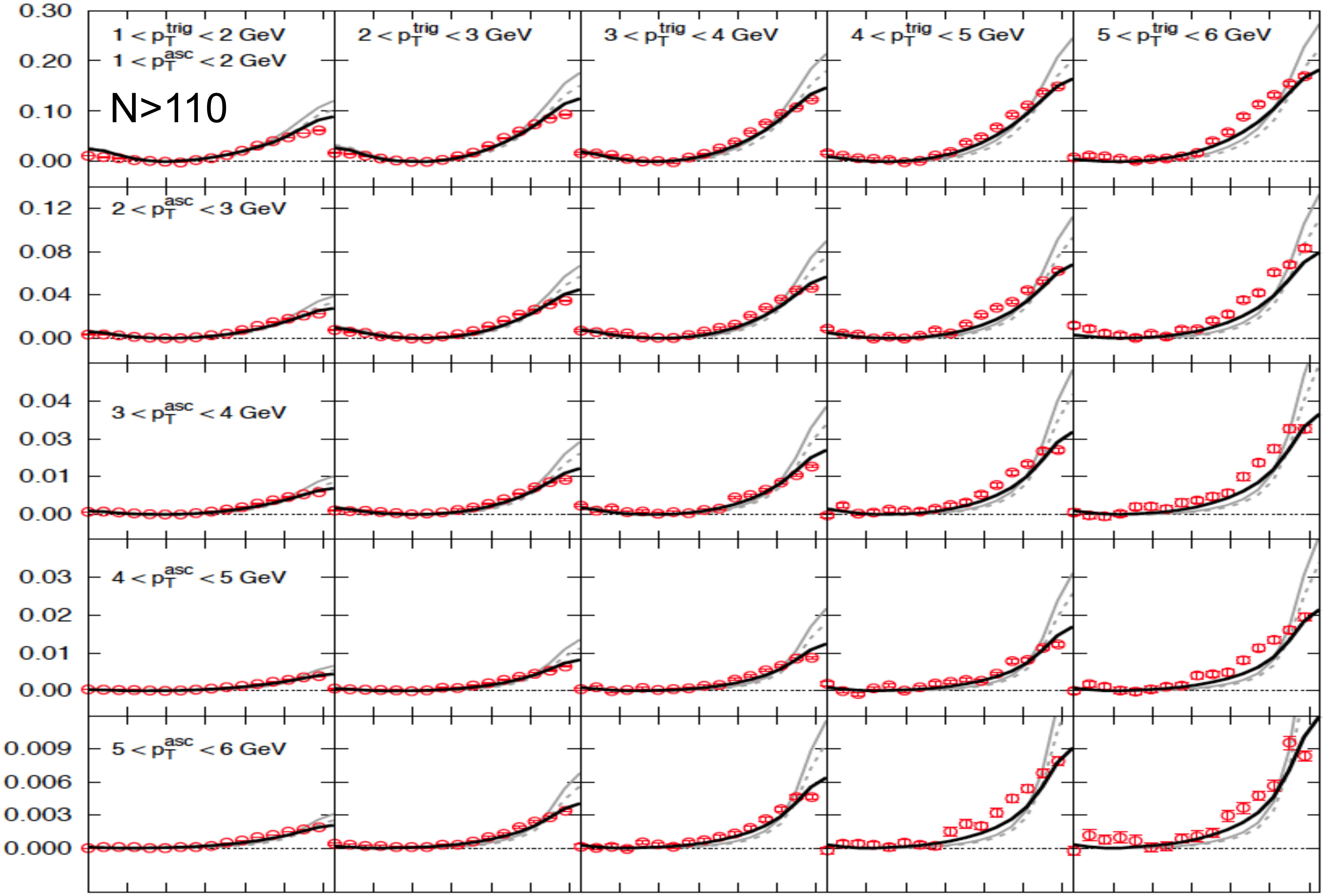


- First principle QCD calculations
- Saturation scale (Q_0) being essentially the only free parameter

Ridge arising from gluon saturation

Correlation functions in pp for various p_T^{trig} and p_T^{assoc}

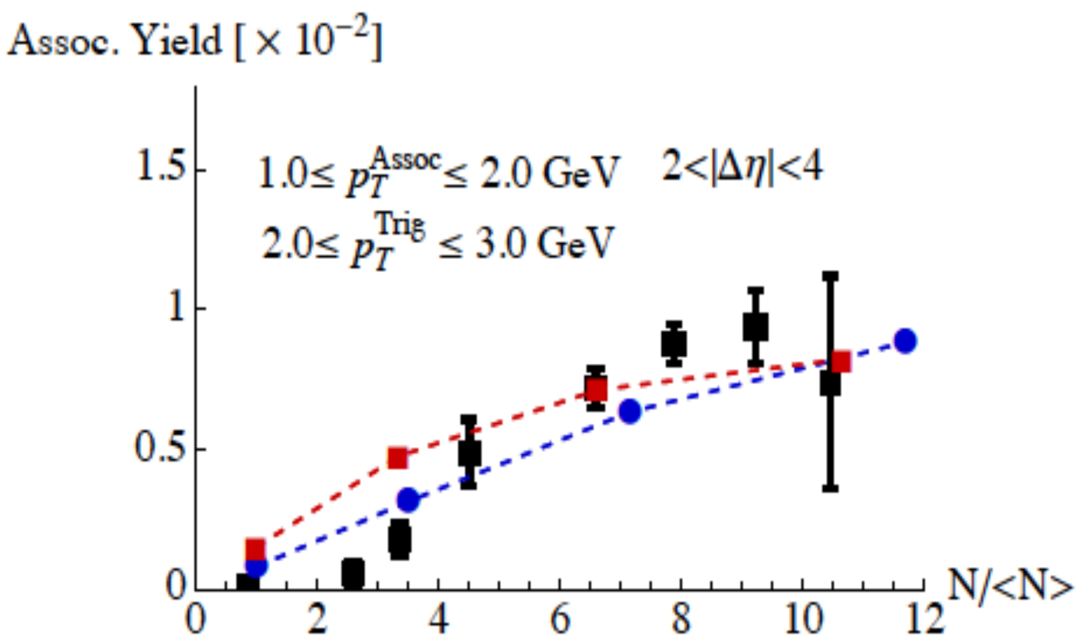
K. Dusling, R. Venugopalan:
arXiv:1211.3701, PRL 108 (2012) 262001



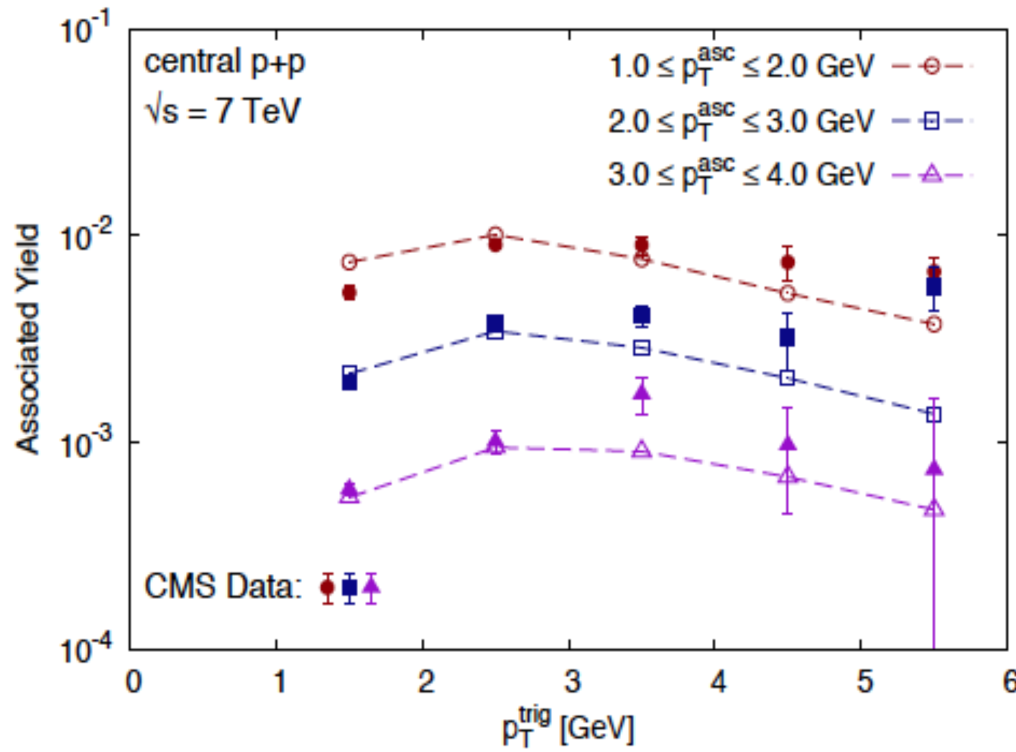
Vey good description of pp ridge data

Ridge arising from gluon saturation

N and p_T dependence of the ridge yield in pp



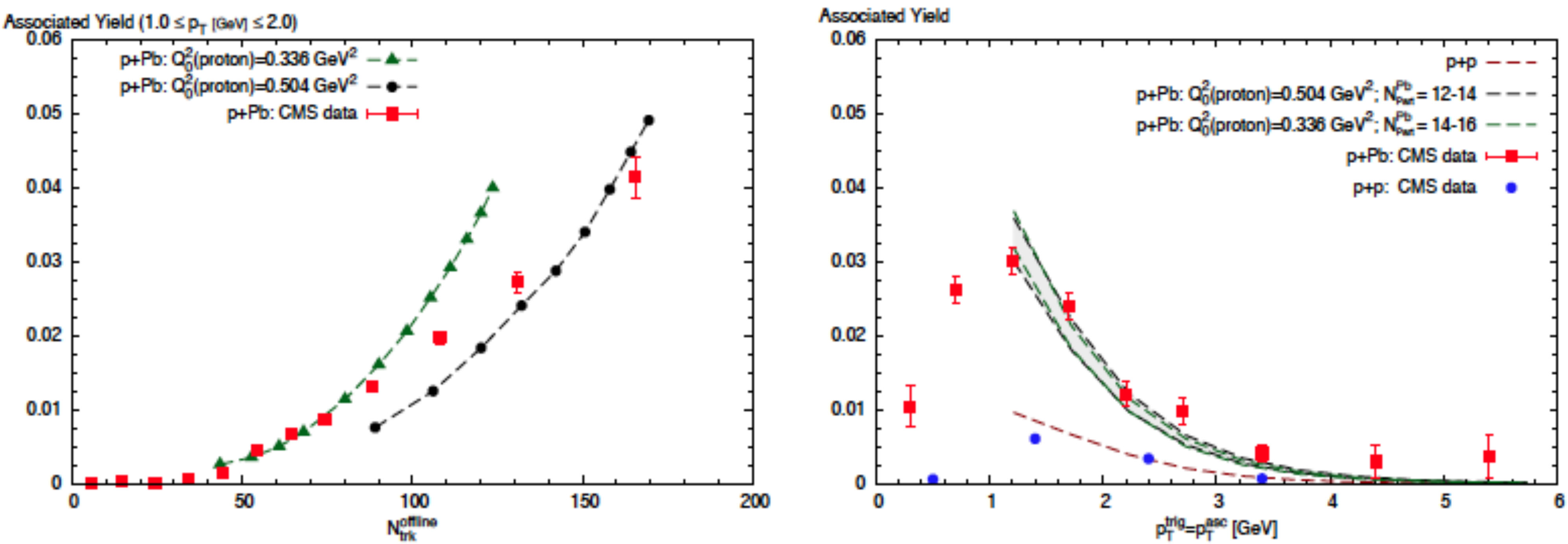
K. Dusling, R. Venugopalan:
arXiv:1211.3701, PRL 108 (2012) 262001



Vey good description of pp ridge data

Ridge arising from gluon saturation

First ridge data in pPb described by the glasma mechanism

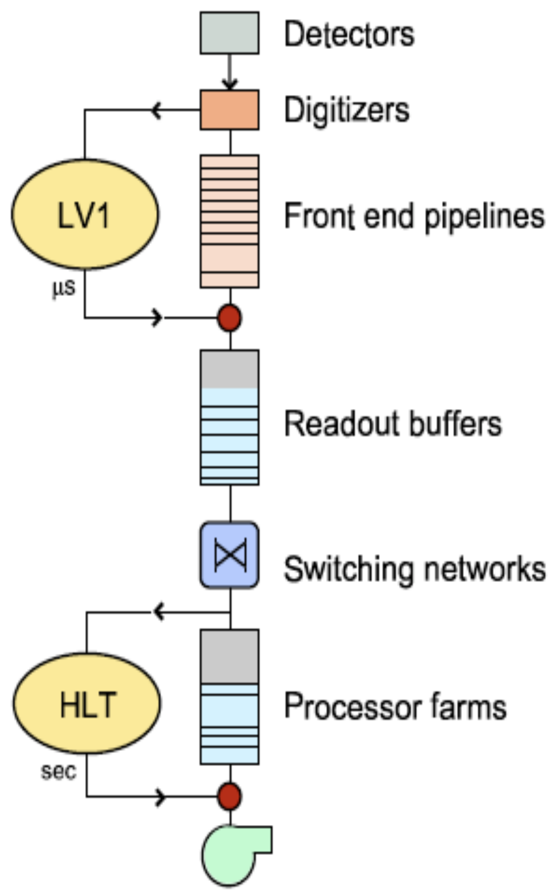


K. Dusling, R. Venugopalan: arXiv:1211.3701

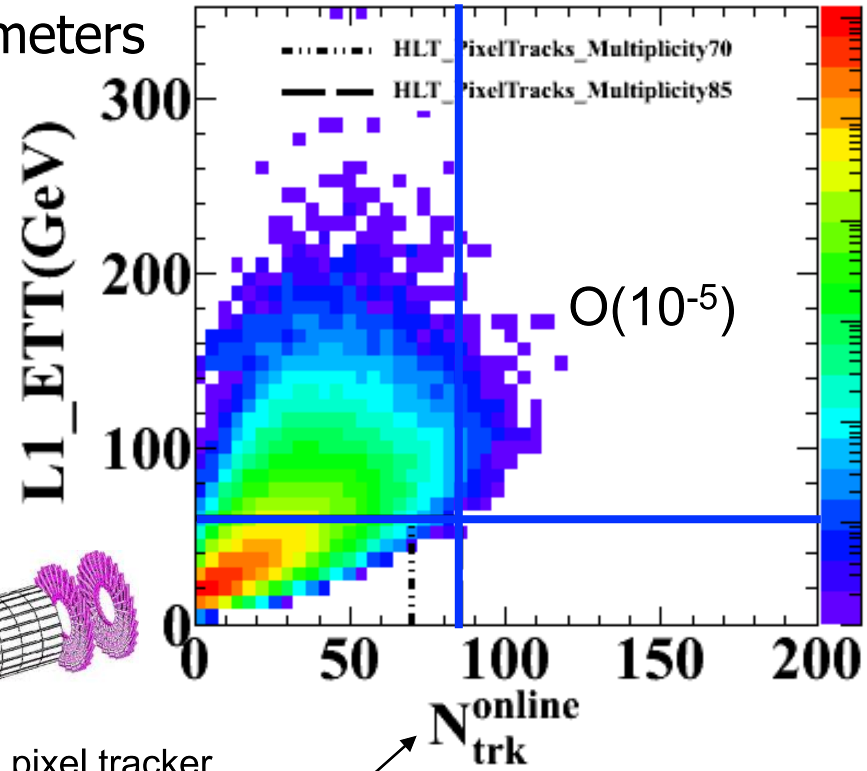
Smoking gun for gluon saturation?

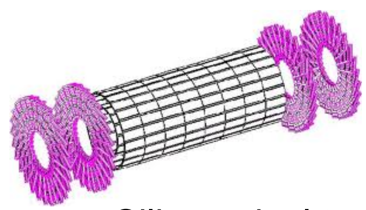
Trigger on high-multiplicity events

CMS trigger and DAQ



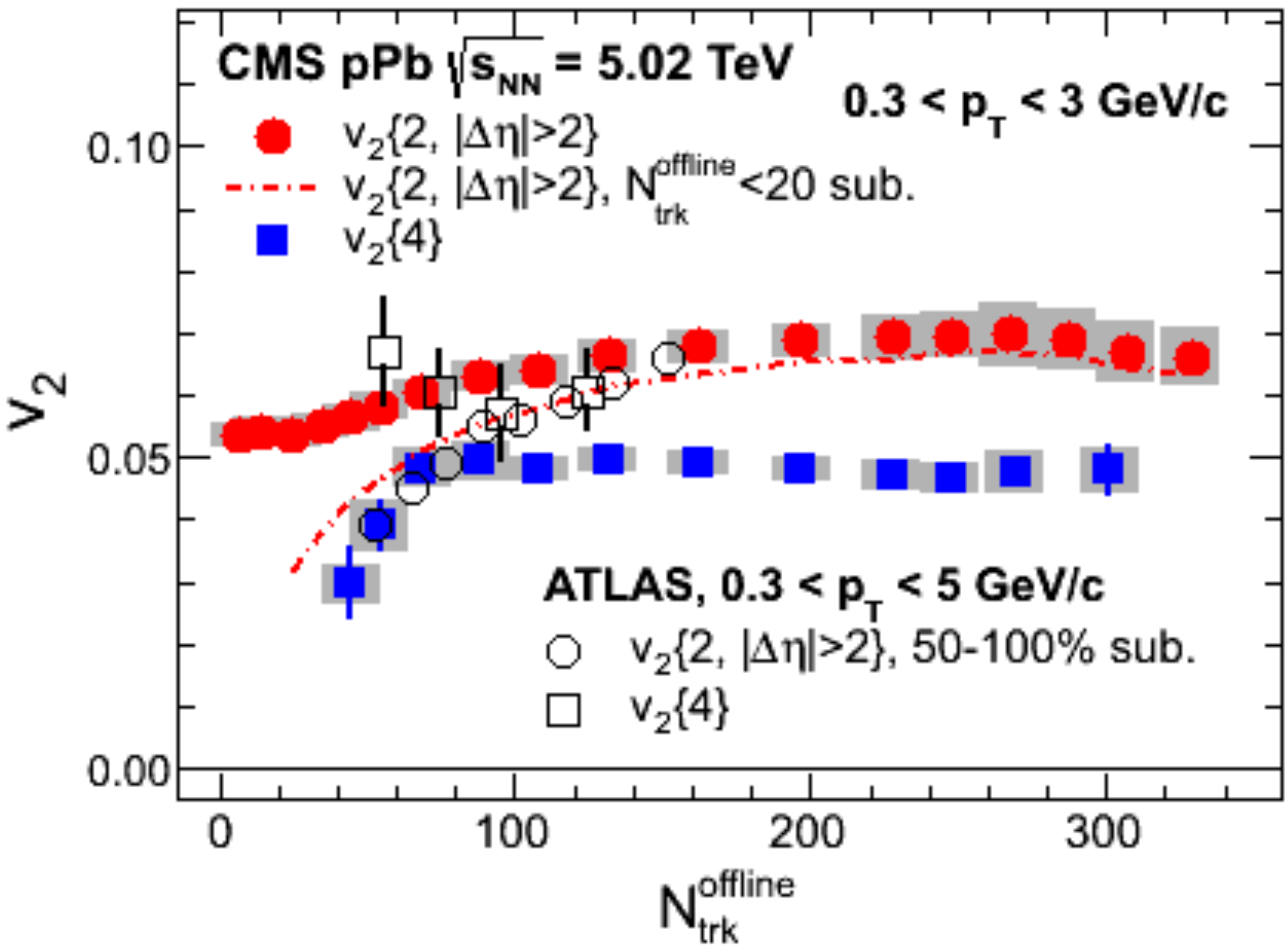
Level-1:
$\sum E_T$> 60 GeV
in calorimeters





Silicon pixel tracker

High-Level trigger:
number of tracks with p_T>0.4 GeV/c, $|\eta|$<2,
within dz<0.12cm of a **single** vertex



CMS pPb $\sqrt{s_{NN}}$ = 5.02 TeV
0.3 < p_T < 3 GeV/c
$v_2\{2, |\Delta\eta|>2\}$
$v_2\{2, |\Delta\eta|>2\}$, $N_{trk}^{offline}$<20 sub.
$v_2\{4\}$
ATLAS, 0.3 < p_T < 5 GeV/c
$v_2\{2, |\Delta\eta|>2\}$, 50-100% sub.
$v_2\{4\}$
v_2
0.10
0.05
0.00
0
100
200
300
$N_{trk}^{offline}$